

# Flow results from ATLAS

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# Large Hadron Collider

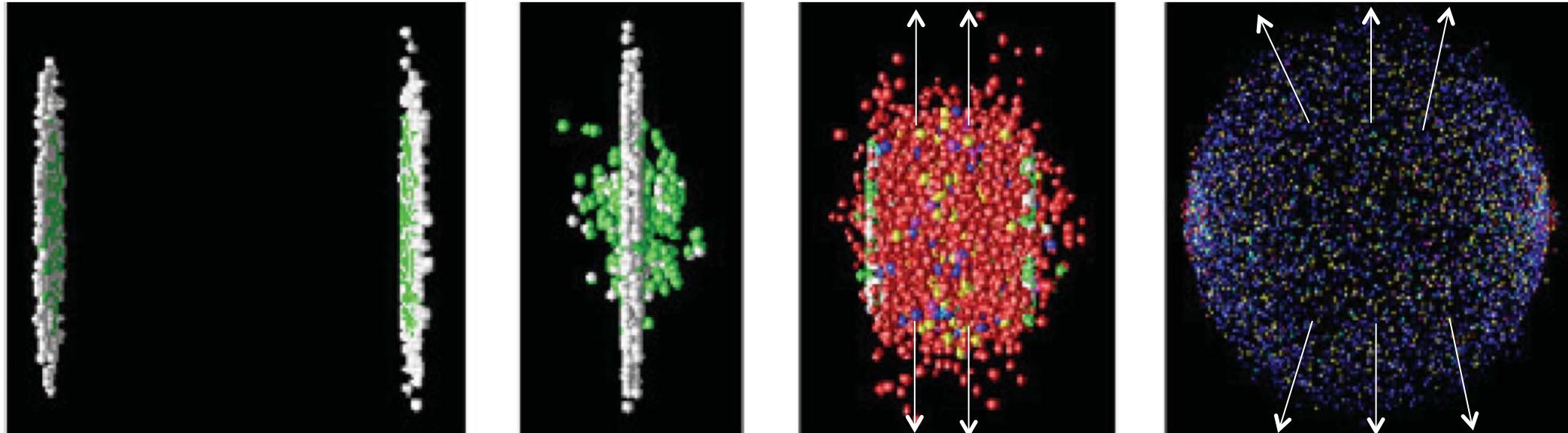
- In addition to p+p collision for particle physics, LHC also carry out high energy nuclear physics research for 1 month/year
  - Pb+Pb collisions at 2.76 TeV, 2010 and 2011
  - p+Pb collisions at 5.02 TeV, 2013

**Focus on Pb+Pb results**



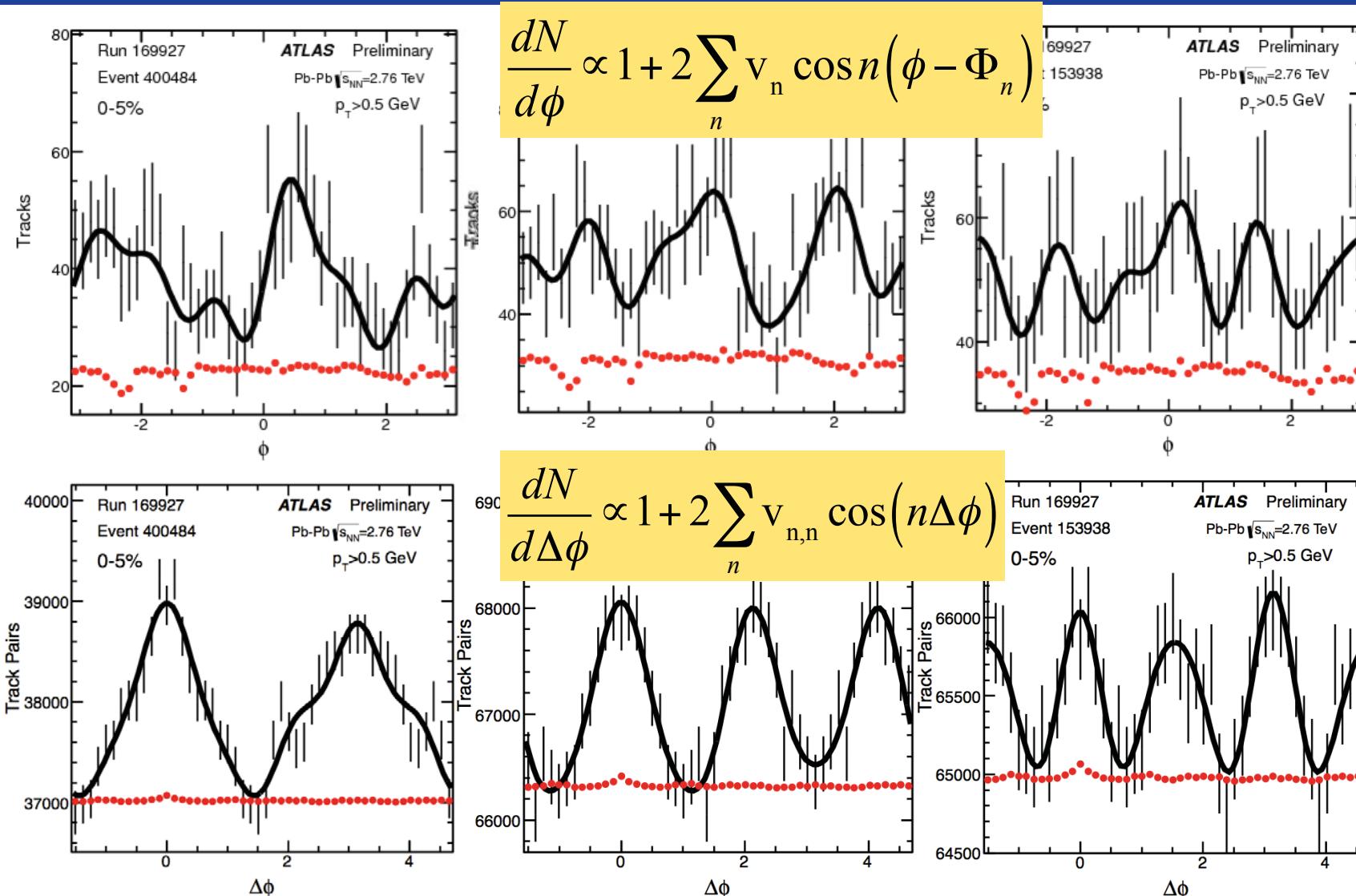
# $^{208}\text{Pb} + ^{208}\text{Pb}$ collisions at 2.76 TeV at LHC

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- Kinetic energy of nuclei =  $1360 \times$  mass energy
- Converted by the strong force (QCD) into particle/entropy production and  $p_T$ : 416 nucleons  $\rightarrow$  25000 particles in an area of few fm across
- Create a transient quark-gluon matter that reach local thermal equilibrium
  - Describe by fluid dynamics (relativistic viscous hydrodynamics)

# Observing the fluid behavior



- Azimuthal “ripples” of little-bangs with rich event-by-event variation
  - Naturally expanded in Fourier series.
- Observed amplitude is sensitive to viscous damping.

# Quark-gluon matter behaves like perfect fluid

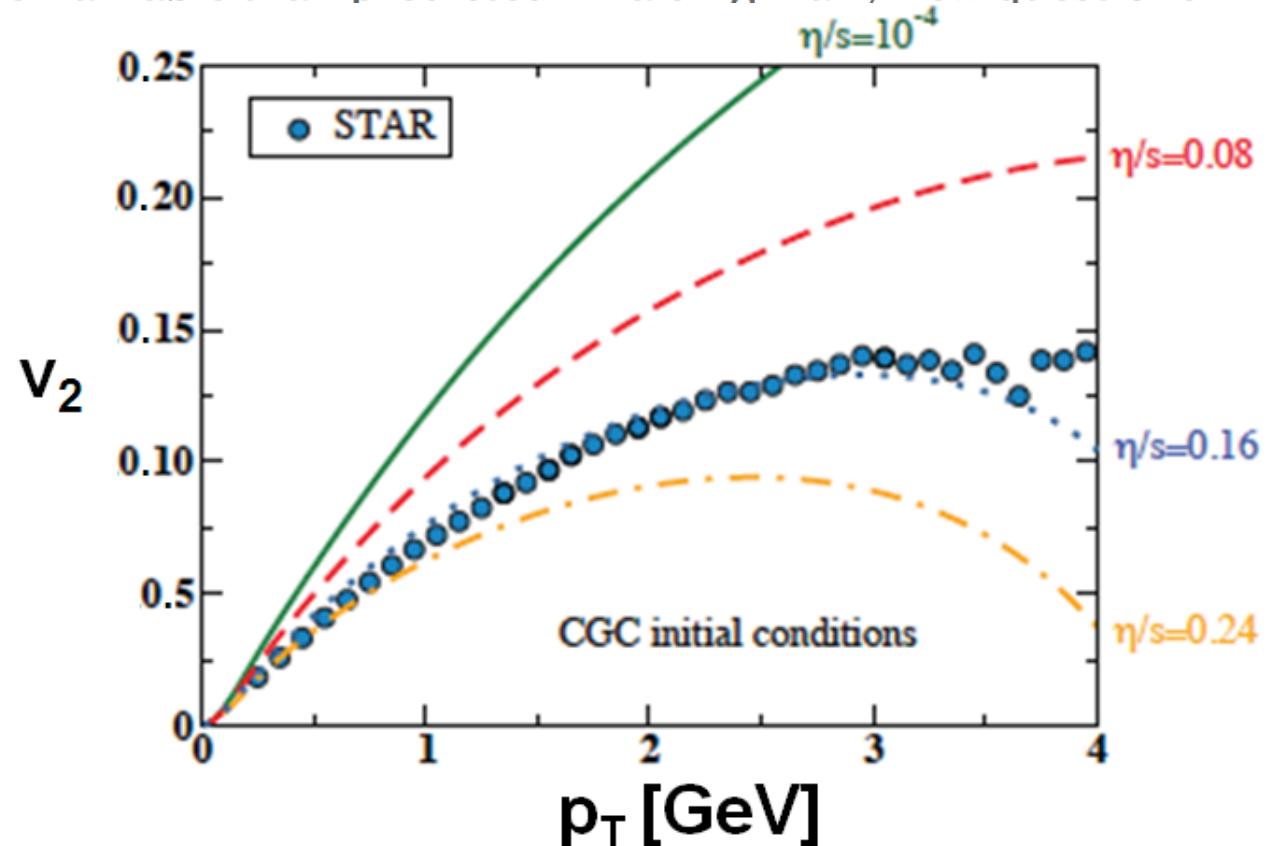
## RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

Monday, April 18, 2005

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Phi)$$

$$\frac{\eta}{s} \sim \text{few} \times \frac{1}{4\pi}$$

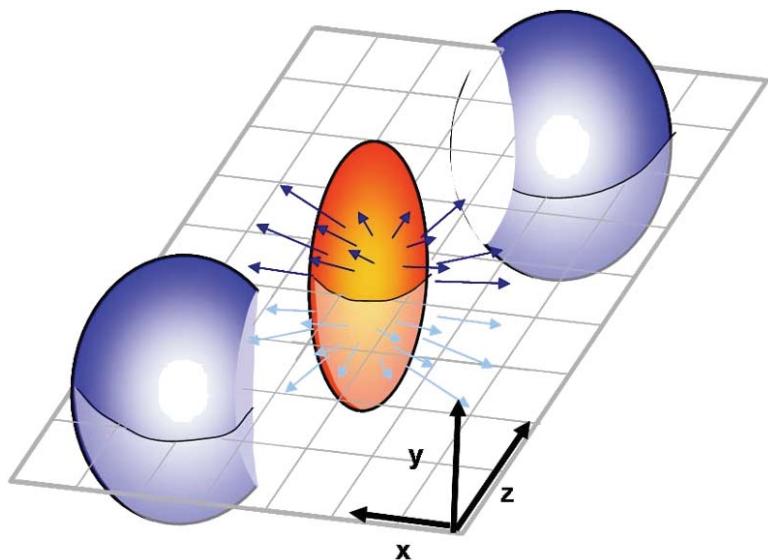


- Large observed amplitude implies small shear viscosity
  - Confirmed by the LHC experiments

Flow is the experimental tool for understand the collective behavior of the QCD matter and infer its transport properties.

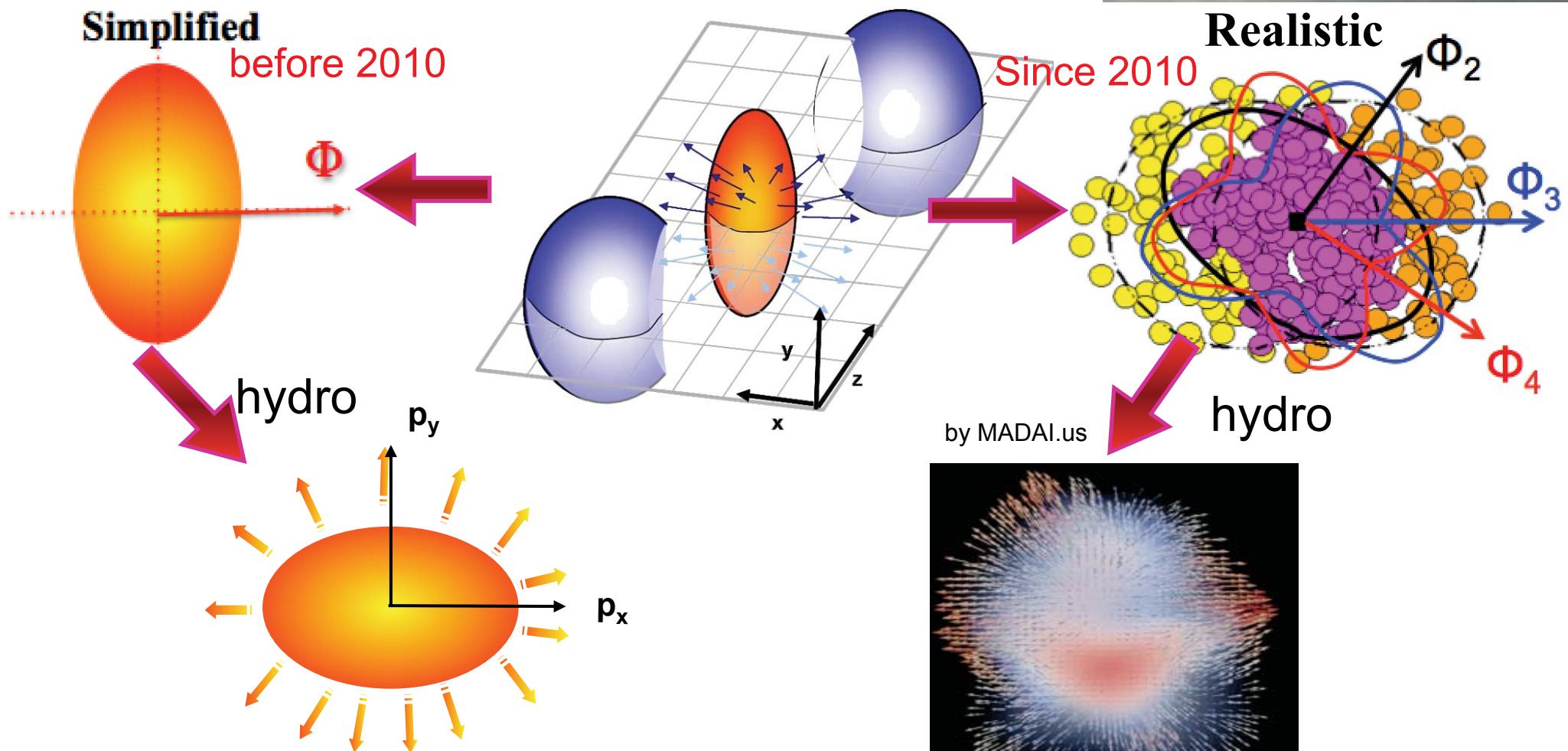
# Flow & initial geometry

What seeds the “ripples”?



# Flow & initial geometry

What seeds the “ripples”?



$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Phi)$$

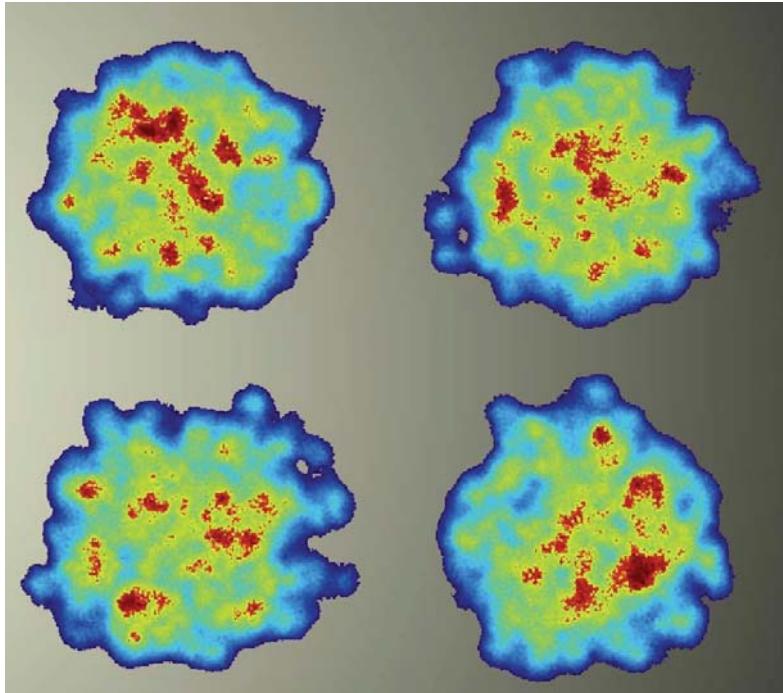
$$\frac{dN}{d\phi} \propto 1 + 2 \sum_n v_n \cos n(\phi - \Phi_n)$$

# Flow observables

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_n v_n \cos n(\phi - \Phi_n)$$

$$\frac{dN}{d\Delta\phi} = \left[ \frac{dN}{d\phi_a} * \frac{dN}{d\phi_b} \right] \propto 1 + 2 \sum_n v_n^a v_n^b \cos(n\Delta\phi)$$

Many little-bang events



Event averaged values:

$$v_n(cent, p_T, \eta)$$

Probability distributions:

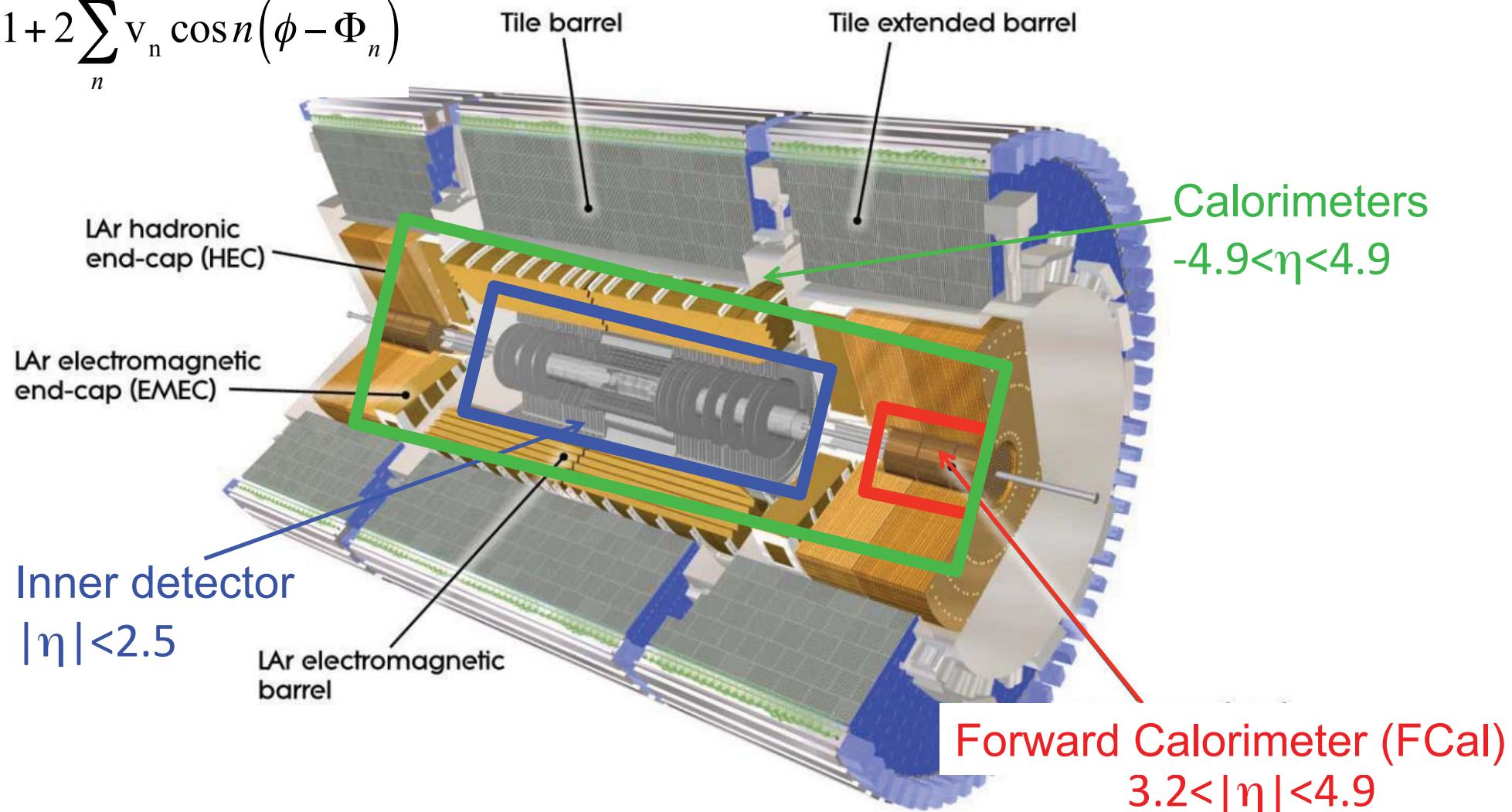
$$p(v_n, v_m, \dots, \Phi_n, \Phi_m, \dots)$$

- EbyE  $v_n$ :  $p(v_2)$ ,  $p(v_3)$  and  $p(v_4)$
- Event plane correlation:  
 $p(\Phi_n, \Phi_m)$  and  $p(\Phi_n, \Phi_m, \Phi_L)$

Probes: initial geometry and transport properties of the QGP

# Observables at detector level

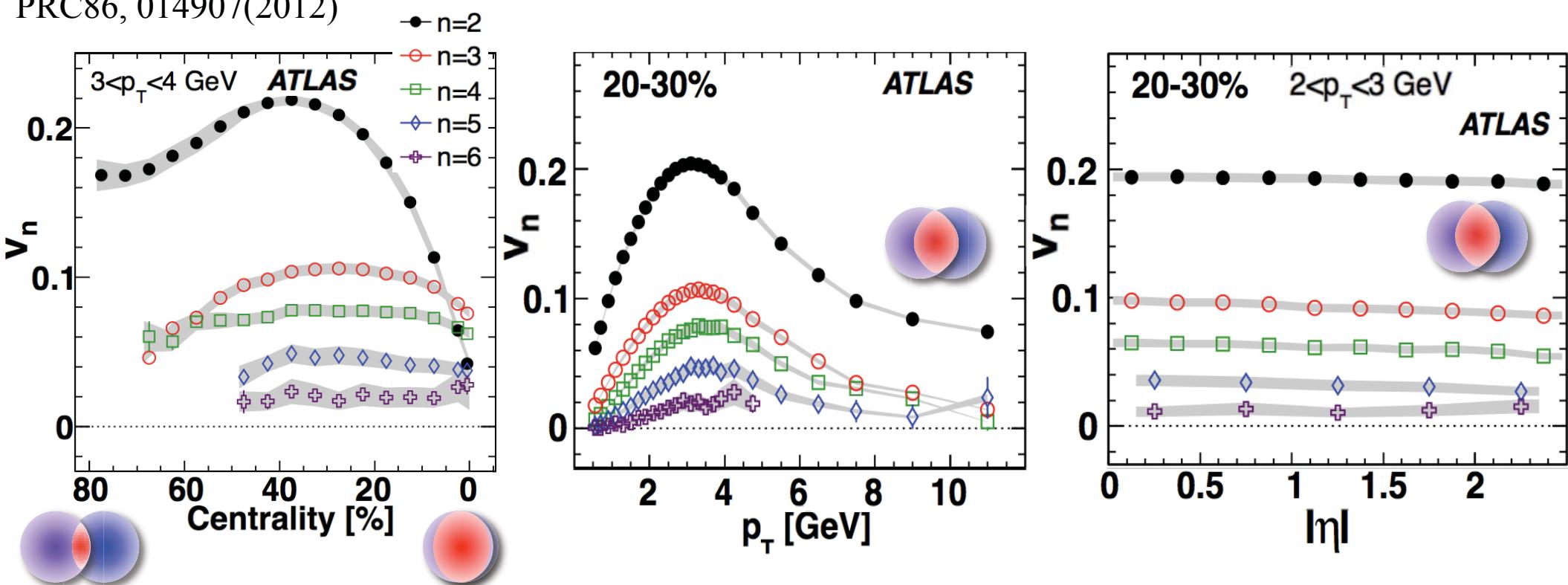
$$\frac{dN}{d\phi} \propto 1 + 2 \sum_n v_n \cos n(\phi - \Phi_n)$$



- $E_T$  in forward calorimeter  $3.2 < |\eta| < 4.9 \rightarrow$  Event plane  $\Phi_n$
- Tracks in inner detector  $|\eta| < 2.5 \rightarrow v_n$  &  $p(v_n)$  measurement
- $E_T$  in calorimeter  $-4.9 < \eta < 4.9 \rightarrow p(\Phi_n, \Phi_m, \dots)$

# Summary of $v_n(\text{cent}, p_T, \eta, n)$

PRC86, 014907(2012)

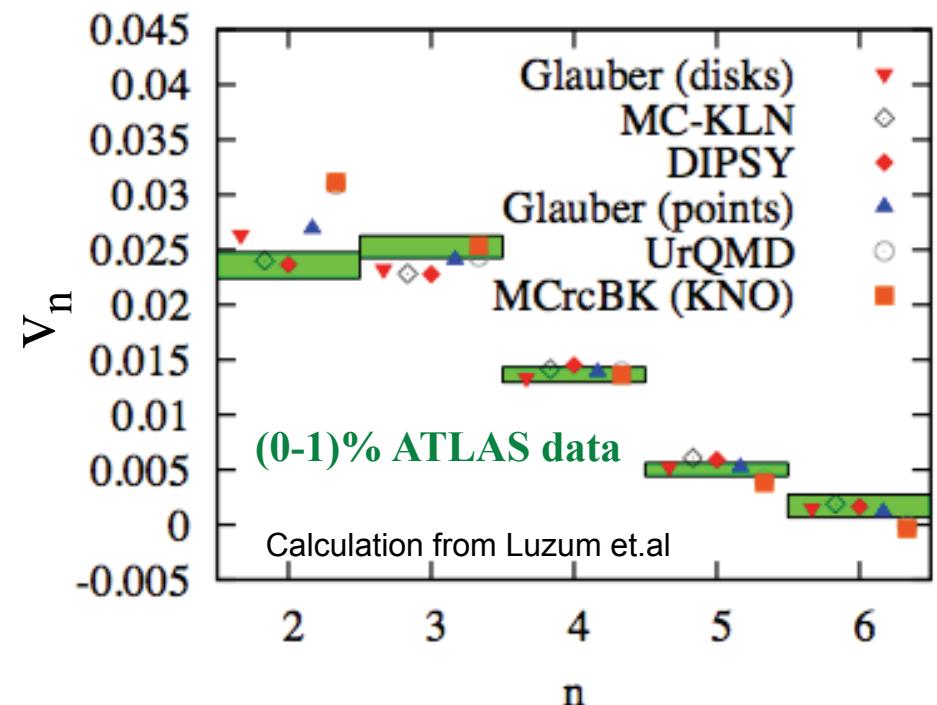
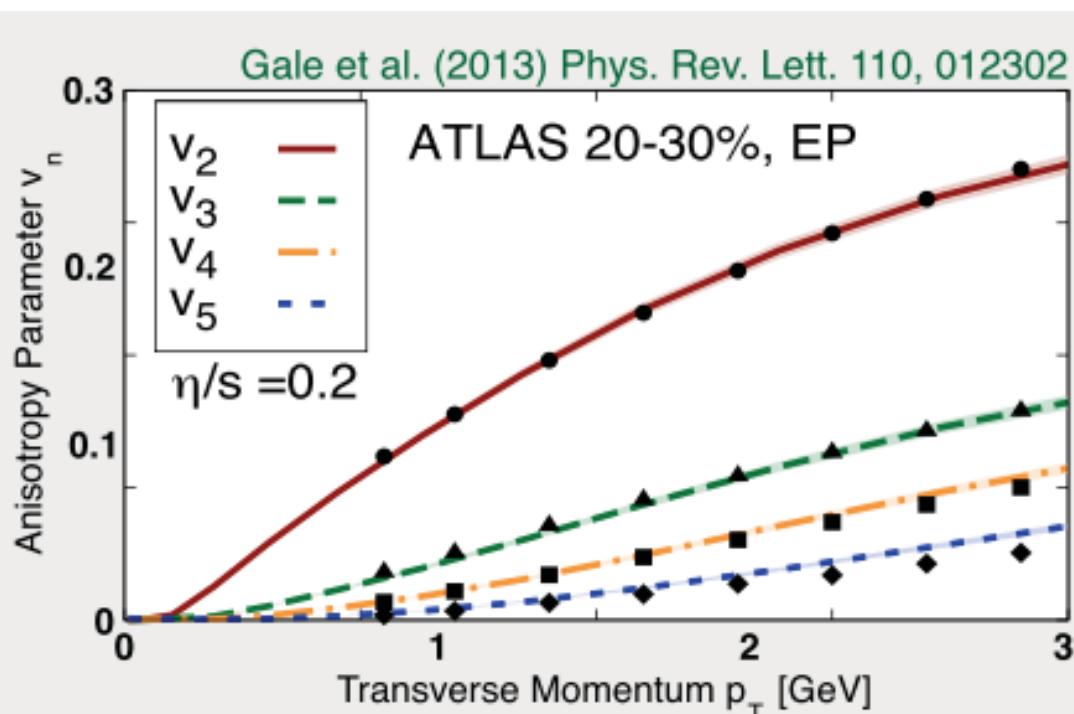


- Features of Fourier coefficients

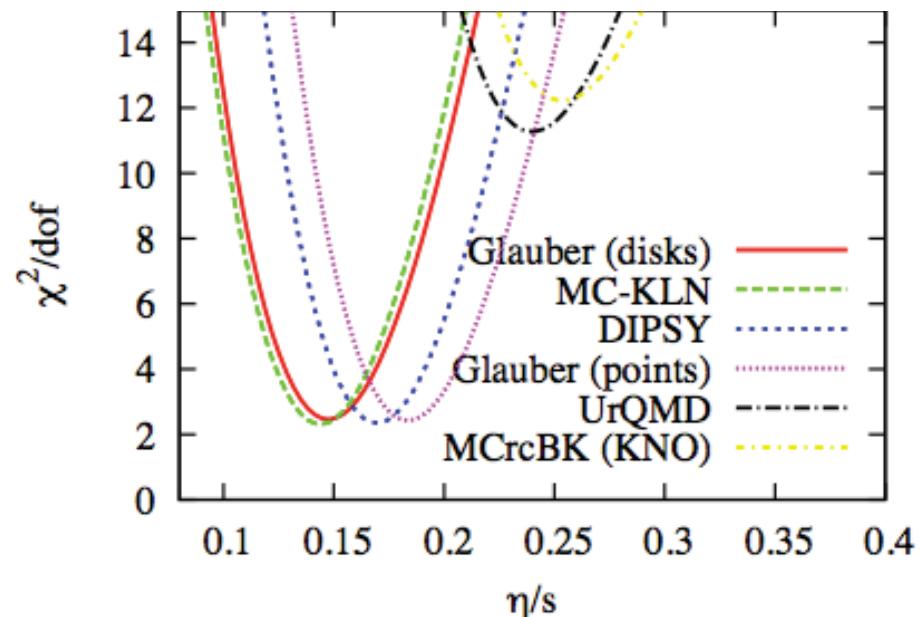
- $v_n$  coefficients rise and fall with centrality  $\rightarrow$  collision geometry
- $v_n$  coefficients rise and fall with  $p_T$ .  $\rightarrow$  hydrodynamic response
- $v_n$  coefficients are  $\sim$ boost invariant.  $\rightarrow$  event shape is global

# Comparison of $v_n$ results with hydro models

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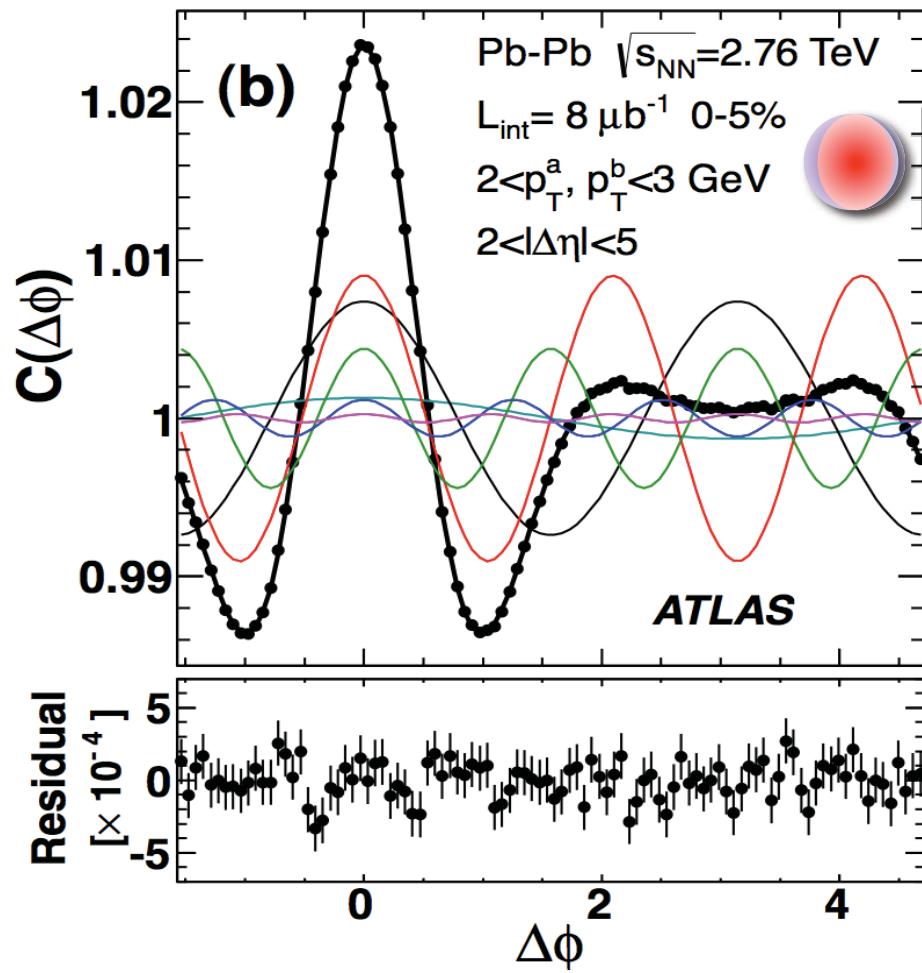
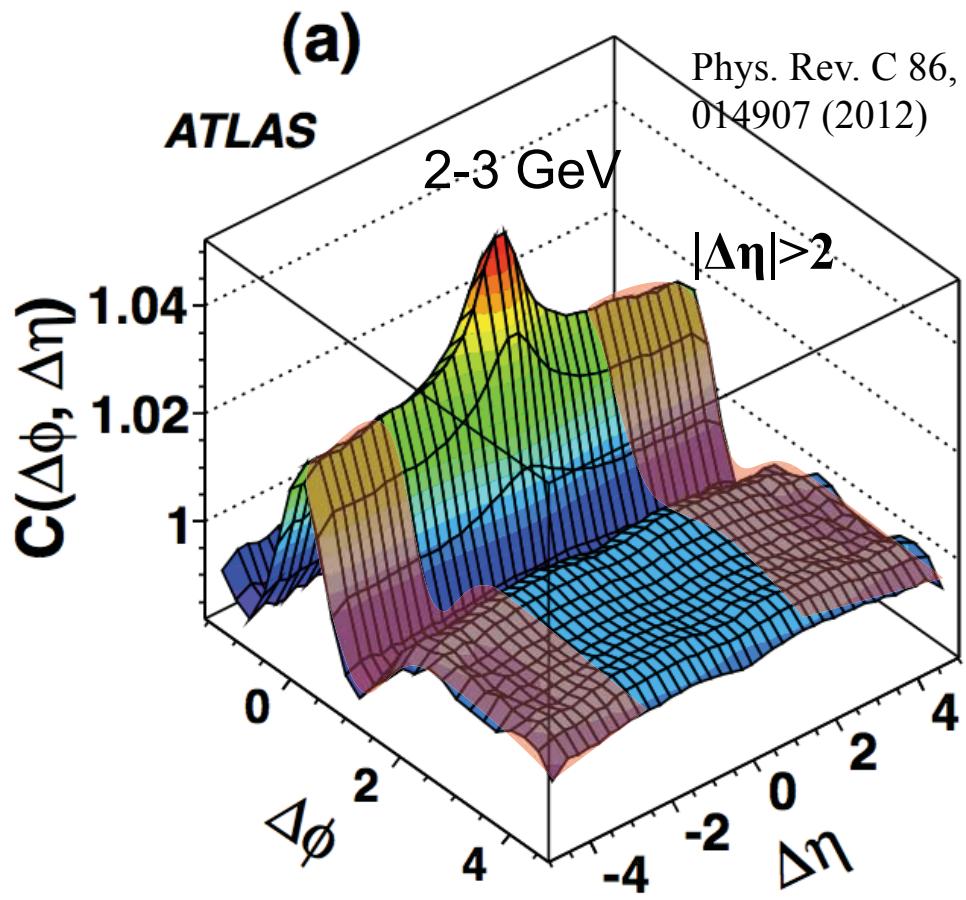


Constrain  $\eta/s$  & initial geometry



# $v_n$ extraction via two-particle correlations (2PC) <sup>11</sup>

$$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2v_{n,n}(p_T^a, p_T^b) \cos(n\Delta\phi) \quad v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b) + \text{non-flow}$$

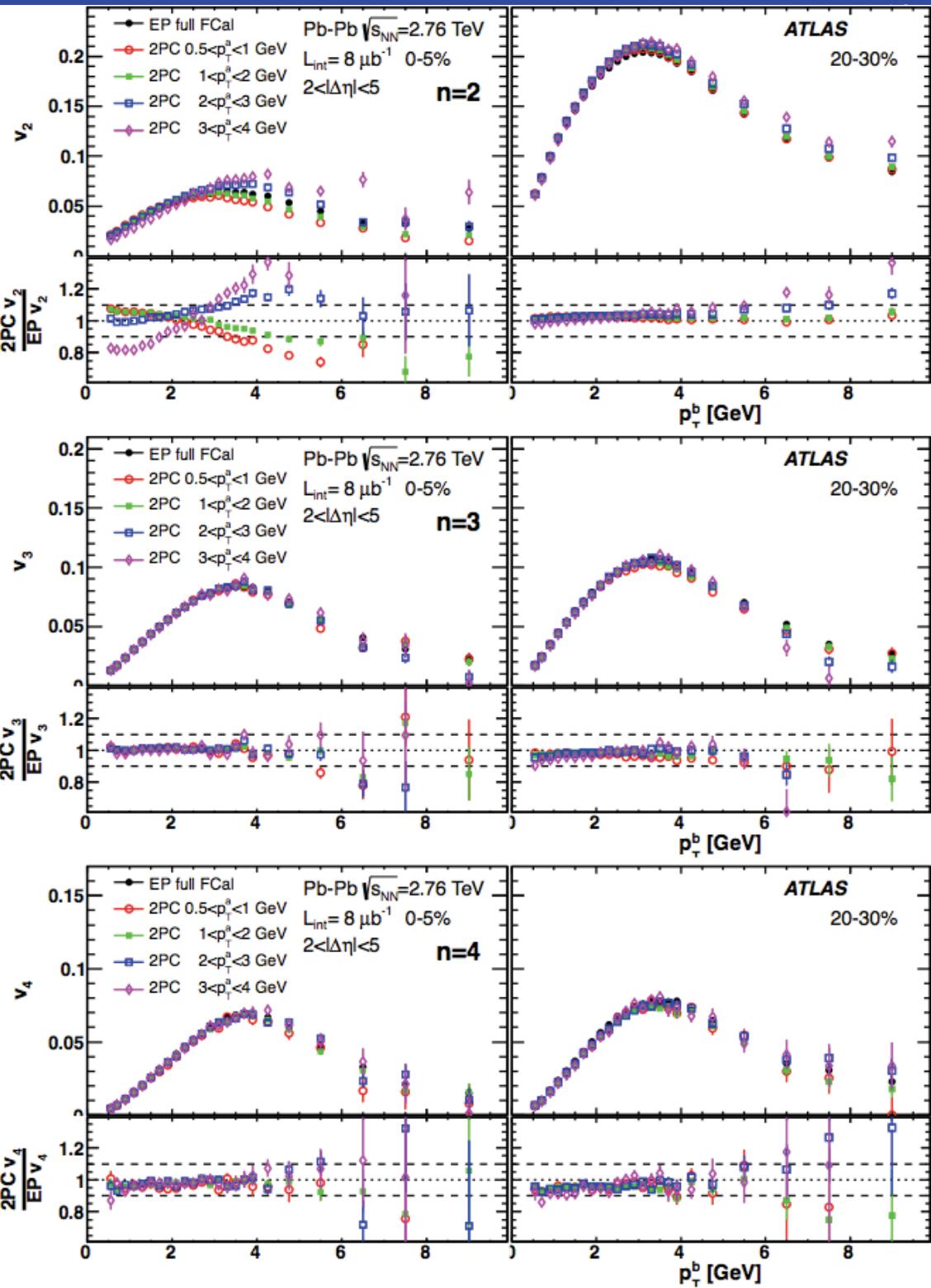


- Long range structures (“ridge”) described by harmonics  $v_{1,1}-v_{6,6}$

# Factorization behavior

$$v_{n,n}(p_T^a, p_T^b) \stackrel{?}{=} v_n(p_T^a) v_n(p_T^b)$$

- Factorization breaks for  $v_1$  due to momentum conservation (later)
  - Extraction of dipolar flow
  
- Factorization breaks for  $v_2$  in central collisions
  - More than 20% for 0-5% most central events!!
  
- Little or no breaking for higher-order  $v_n$



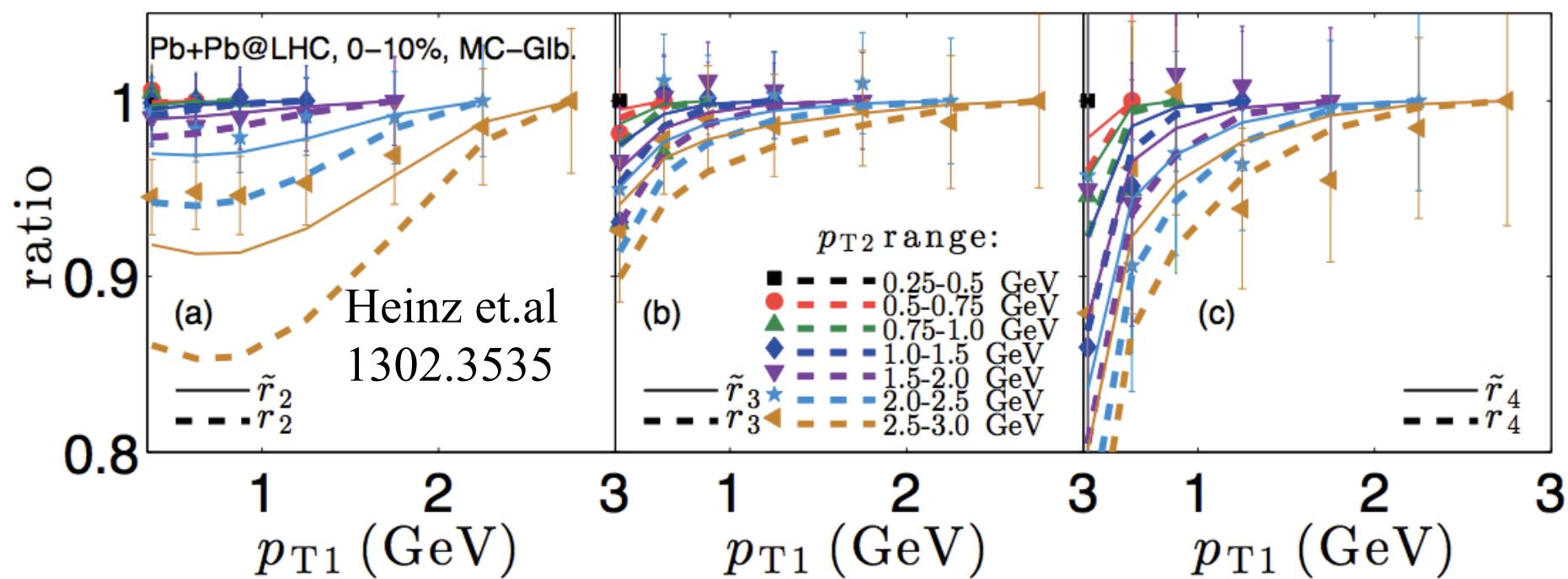
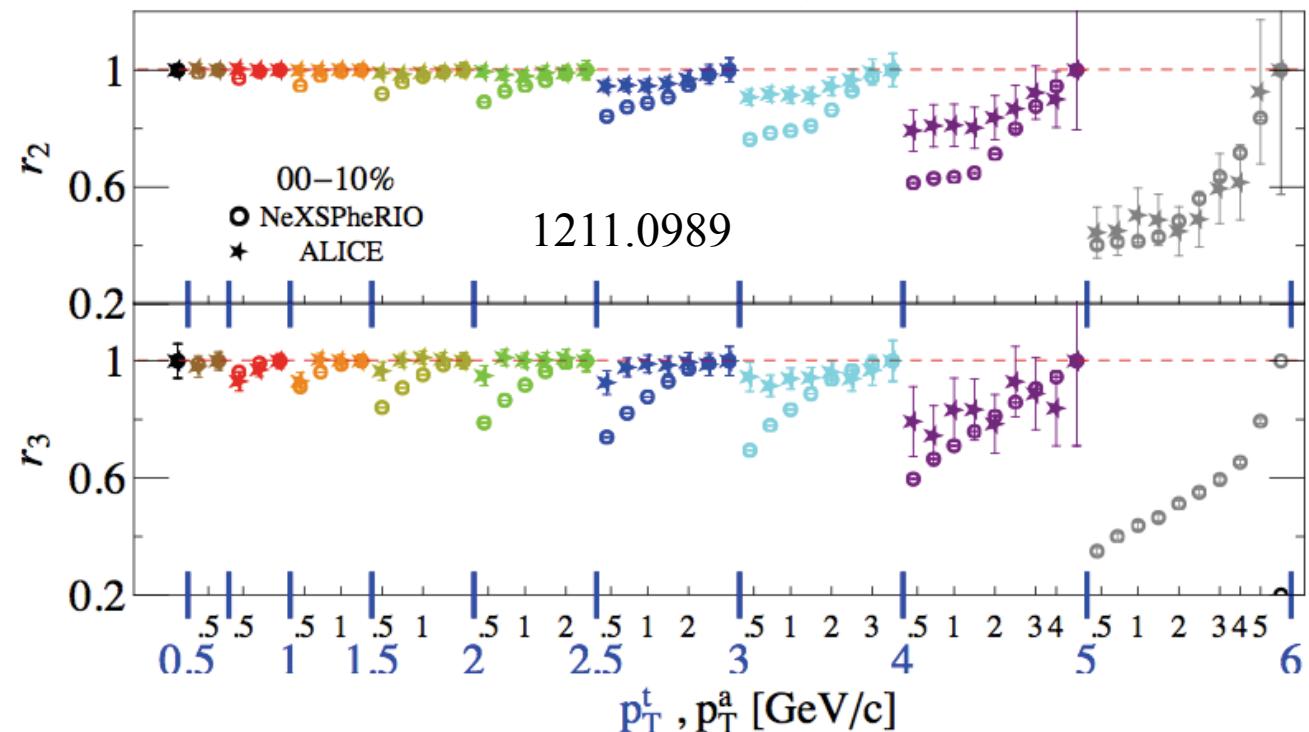
Jean-Yves, Luzum:1211.0989

Heinz Zhi Qiu, Chun Shen 1302.3535

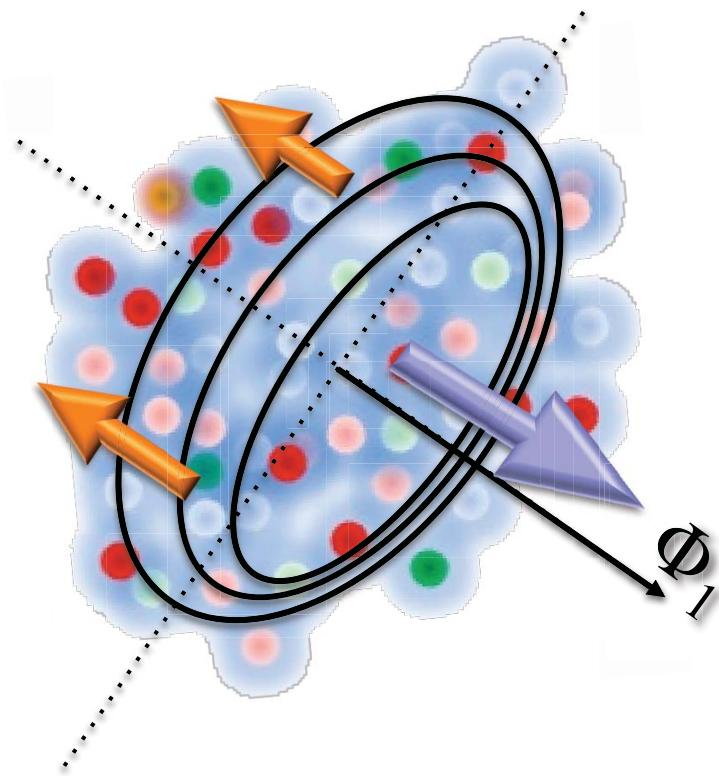
# Hydro prediction

$$r_n \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)V_{n\Delta}(p_T^b, p_T^b)}}$$

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# Dipolar flow $v_1$



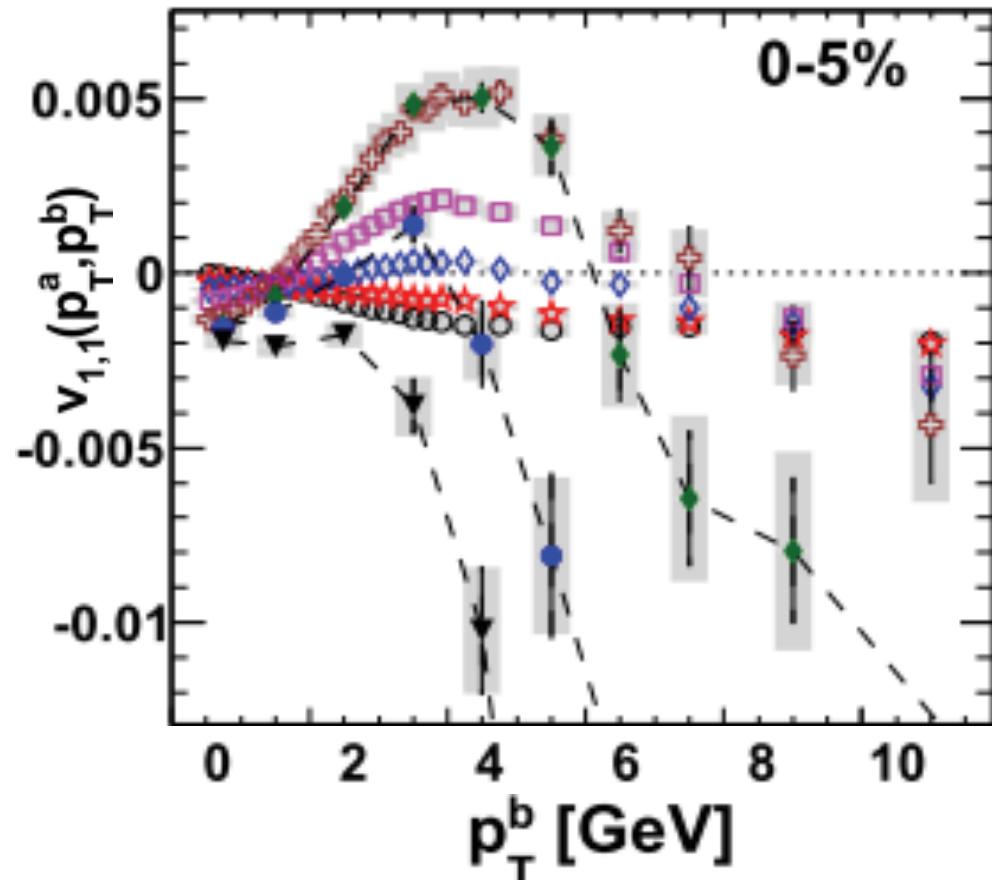
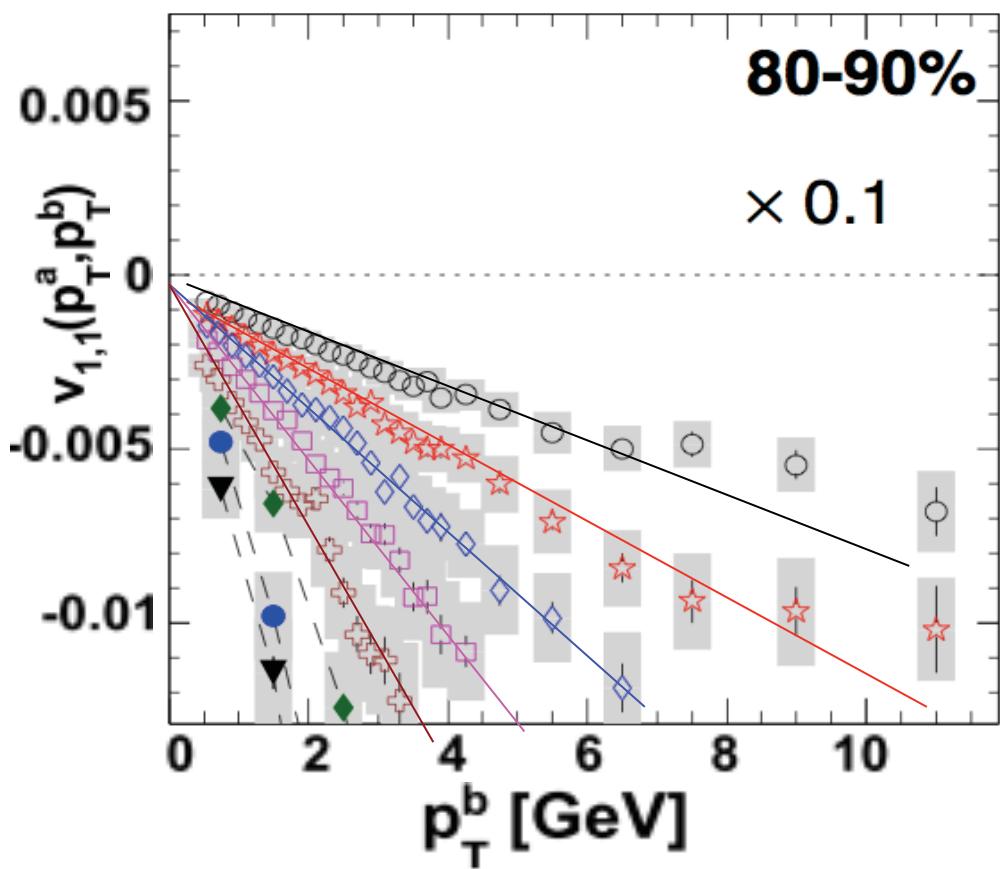
**Dipolar (even component) flow  
~boost invariant in  $\eta$**

**But also include non-flow effects: Momentum of individual particle must be balanced by others:**

$$v_{1,1}(p_T^a, p_T^a) = v_1(p_T^a) v_1(p_T^b) + \text{non-flow} \approx -\frac{p_T^a \times p_T^b}{M \langle p_T^2 \rangle}$$

# Behaviors of $v_{1,1}(p_T^a, p_T^b)$

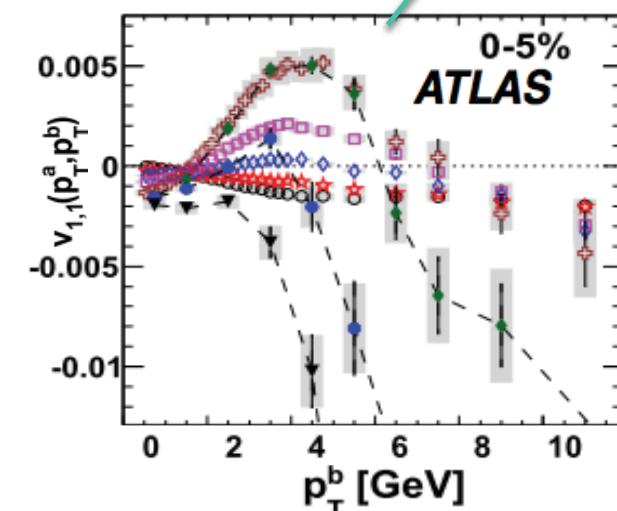
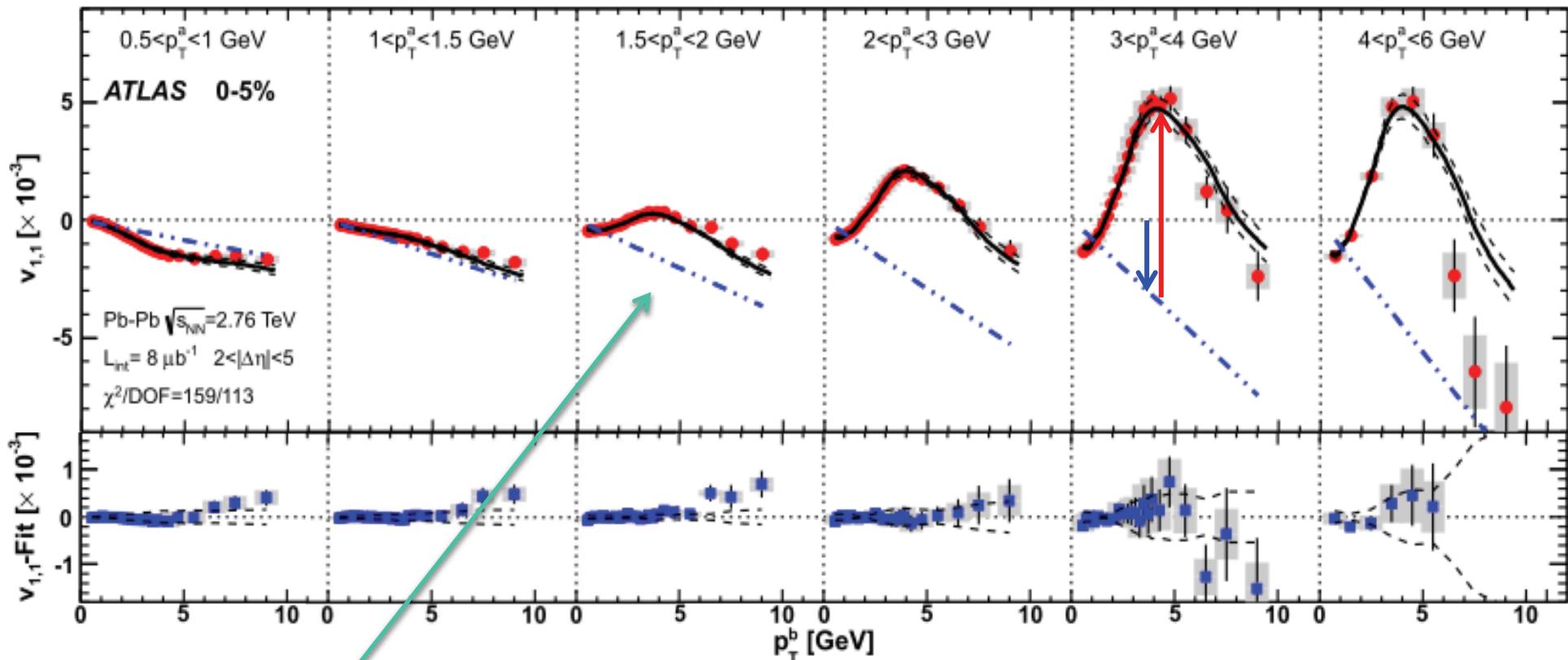
—○—  $0.5 < p_T^a < 1 \text{ GeV}$   
 —●—  $3 < p_T^a < 4 \text{ GeV}$   
 —★—  $1 < p_T^a < 1.5 \text{ GeV}$   
 —◆—  $4 < p_T^a < 6 \text{ GeV}$   
 —◇—  $1.5 < p_T^a < 2 \text{ GeV}$   
 —●—  $6 < p_T^a < 8 \text{ GeV}$   
 —□—  $2 < p_T^a < 3 \text{ GeV}$   
 —▼—  $8 < p_T^a < 20 \text{ GeV}$



**Well described by**  $-\frac{p_T^a \times p_T^b}{M \langle p_T^2 \rangle}$

$$v_{1,1}(p_T^a, p_T^b) \stackrel{?}{=} v_1(p_T^a)v_1(p_T^b) - \frac{p_T^a \times p_T^b}{M \langle p_T^2 \rangle}$$

# Extracting the $\eta$ -even $v_1(p_T)$



$$v_{1,1}(p_T^a, p_T^b) = v_1^{\text{Fit}}(p_T^a)v_1^{\text{Fit}}(p_T^b) - cp_T^a p_T^b$$

**Excellent Fit!**

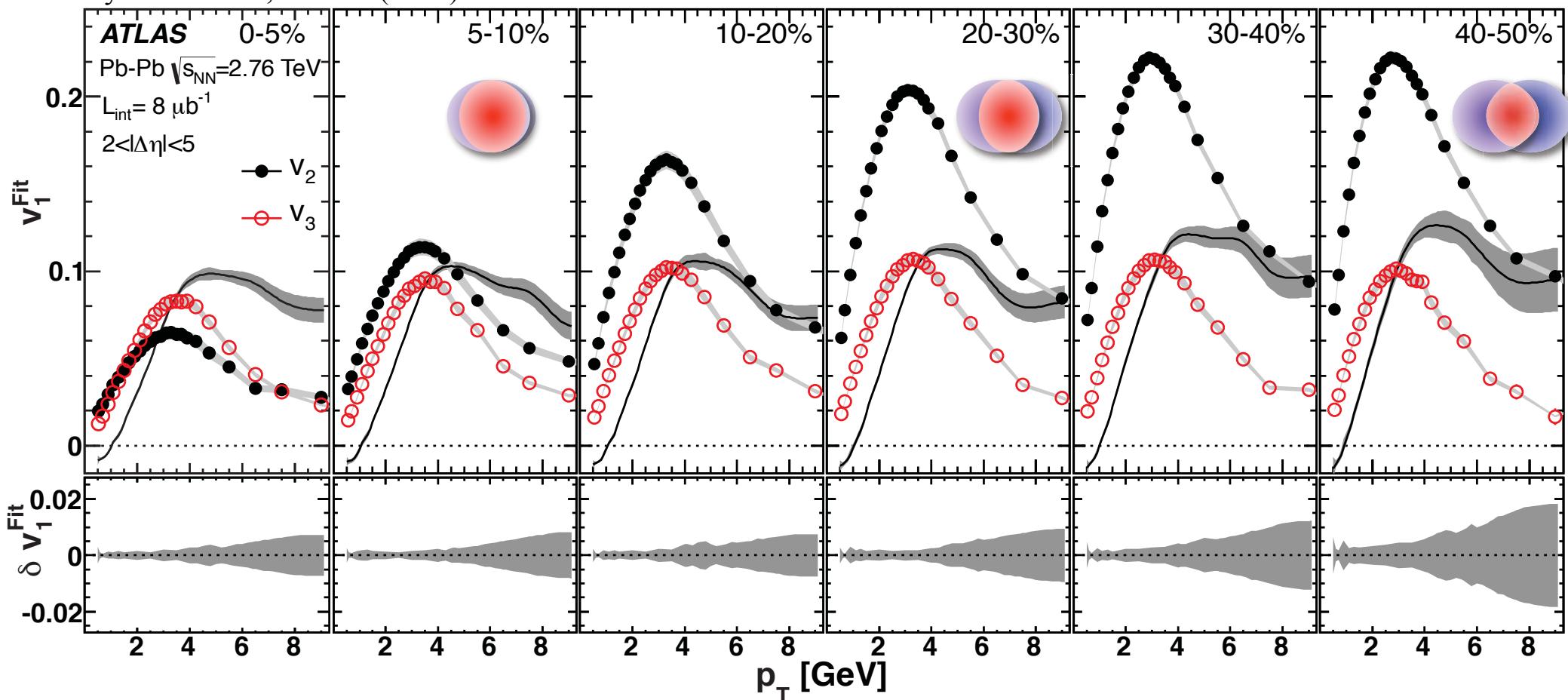
Red Points:  $v_{1,1}$  data

Black line : Fit to functional form

Blue line: momentum conservation component

# Extracted dipolar flow

Phys. Rev. C 86, 014907 (2012)

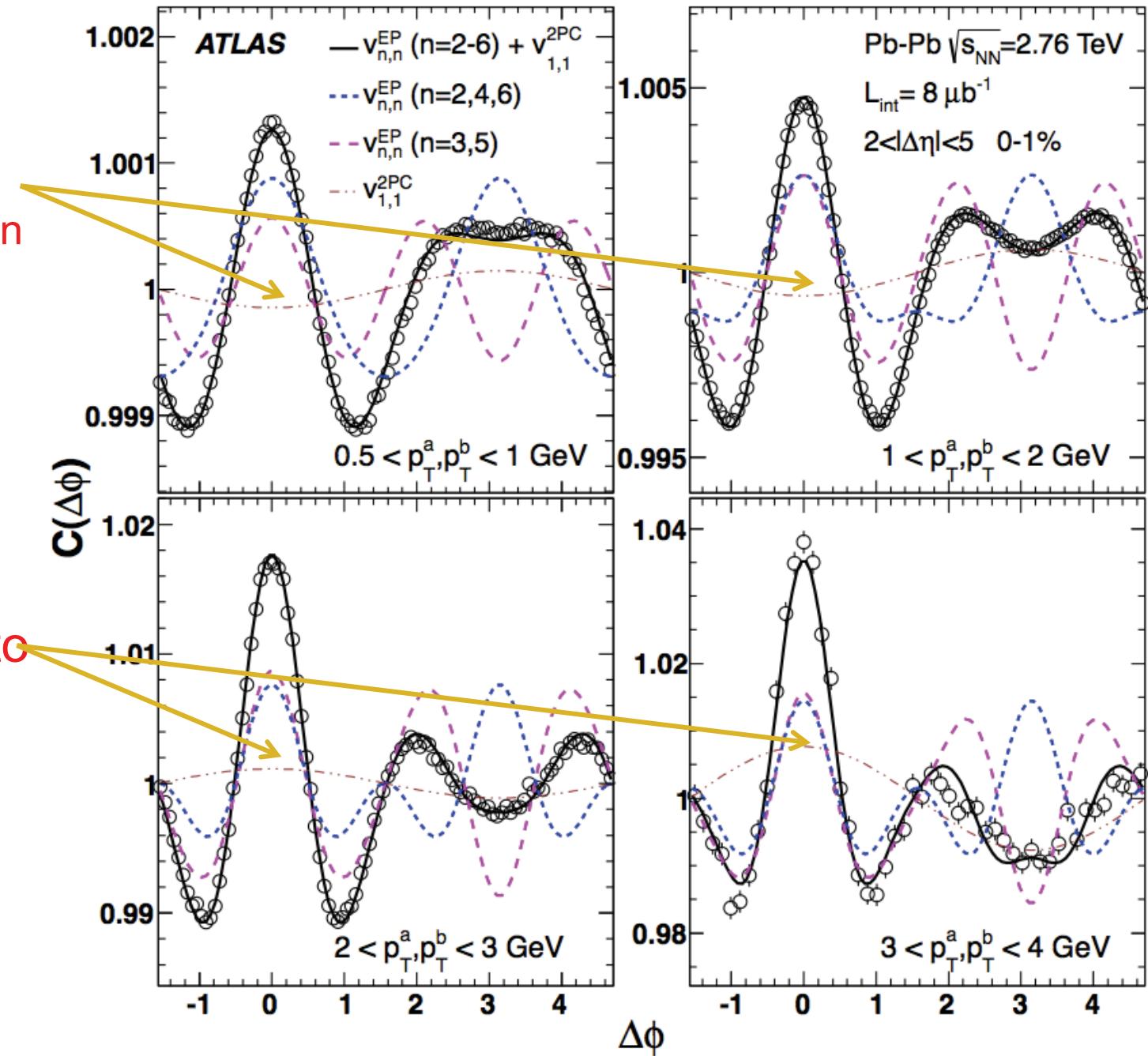


- Negative for  $p_T < 1.0 \text{ GeV} \rightarrow$  expected from hydro calculations
- Similar magnitudes as  $v_3$  but much larger at high  $p_T \rightarrow$  significant dipole deformation in the initial geometry

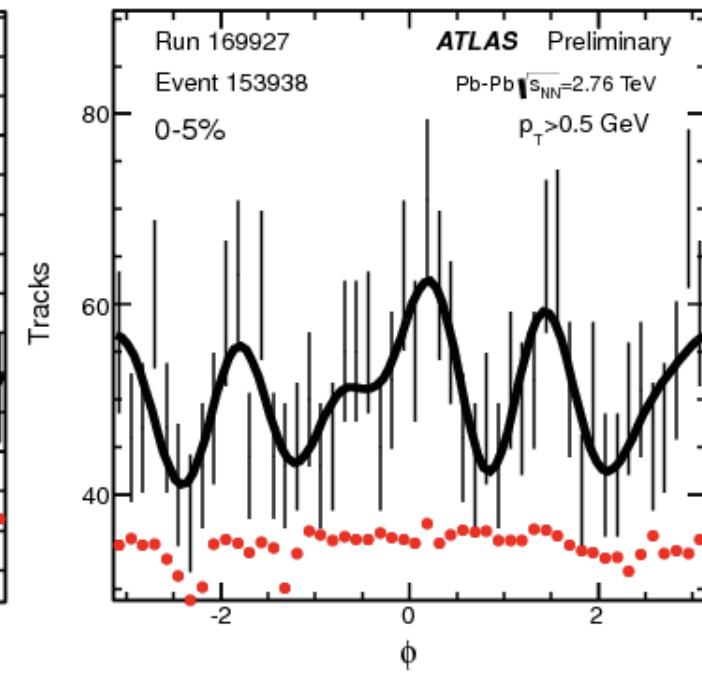
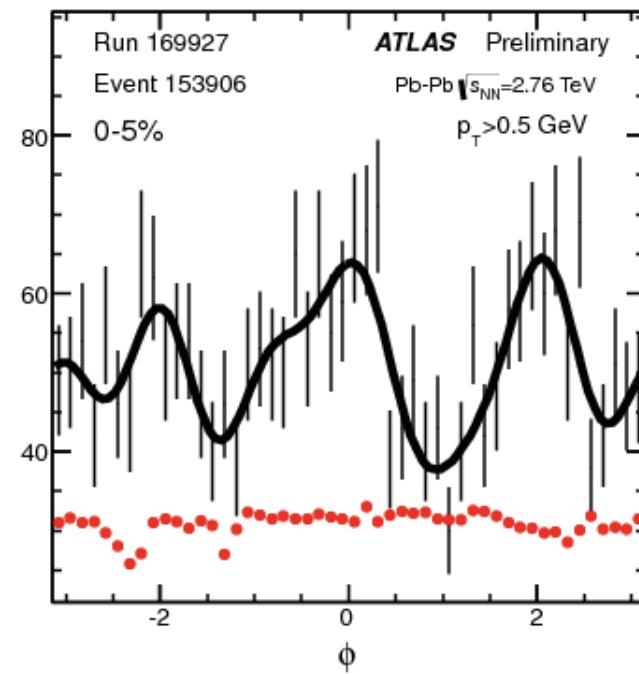
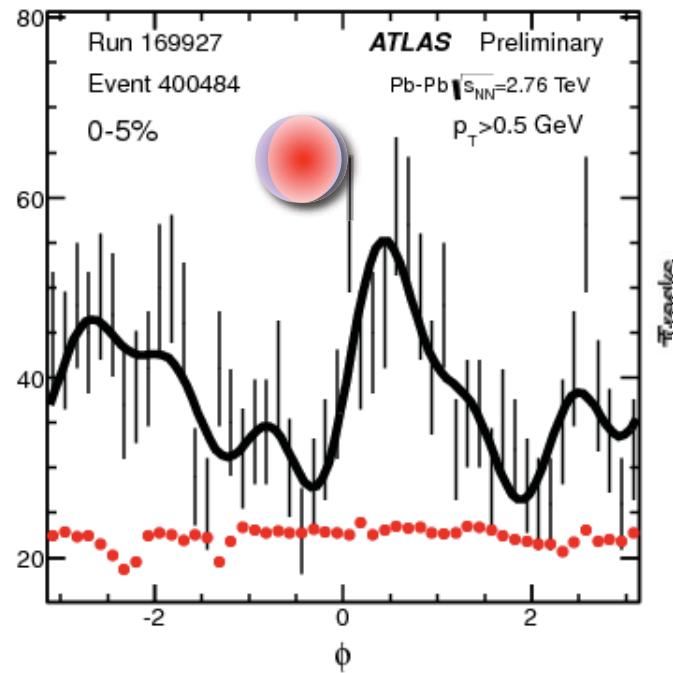
# Importance of dipolar flow for 2PC (0-5%)

$v_{1,1}$  component shown by brown dashed lines

Most of  $v_{1,1}$  is due to momentum conservation



# Event-by-event harmonic flow seen in data



$$\frac{dN}{d\phi} \propto 1 + 2 \sum_n v_n^{\text{obs}} \cos n(\phi - \Phi_n^{\text{obs}})$$

↓  
Obtain  $p(v_n)$  from  $p(v_n^{\text{obs}})$

**response function:**  $p(v_n^{\text{obs}}|v_n)$

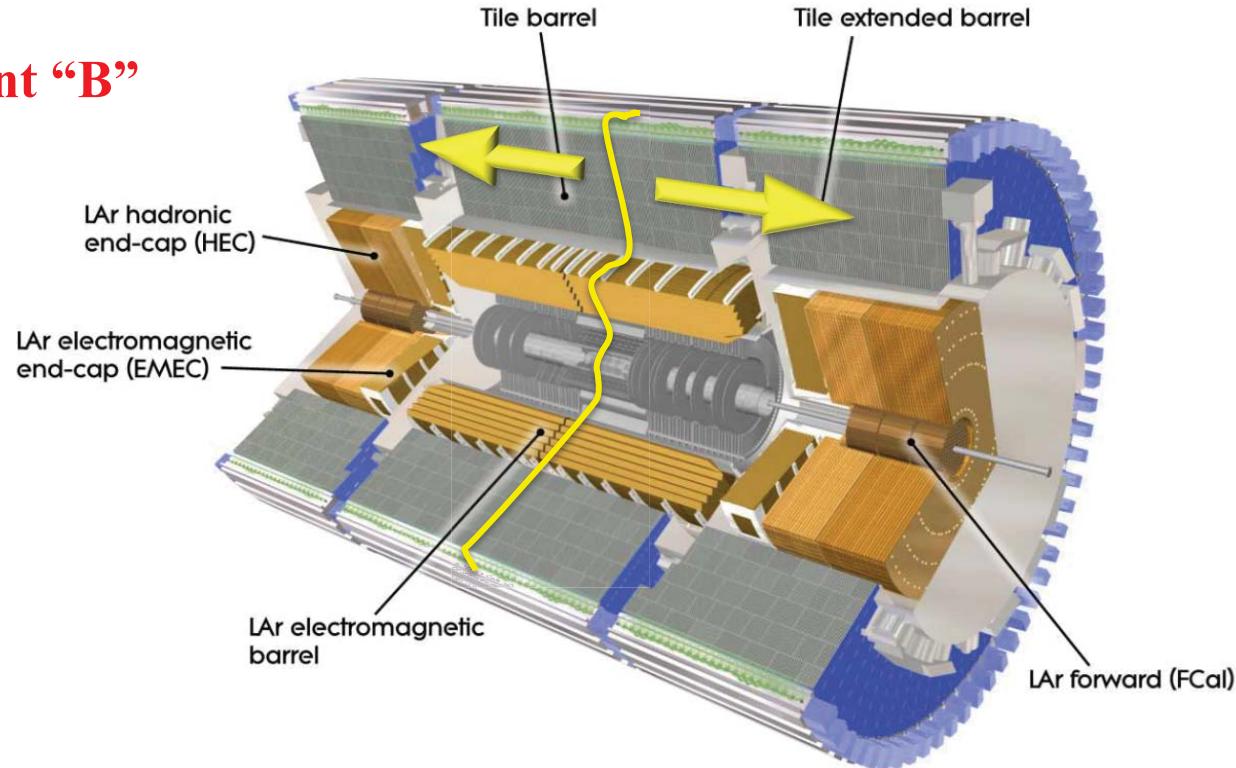
↓  
Obtain  $p(\Phi_n, \Phi_m)$  from  $p(\Phi_n^{\text{obs}}, \Phi_m^{\text{obs}})$

Determine resolution corrections

ATLAS-CONF-2012-49

# How to extract $p(v_n^{\text{obs}}|v_n)$ ?

Sub-event “A” - Sub-event “B”

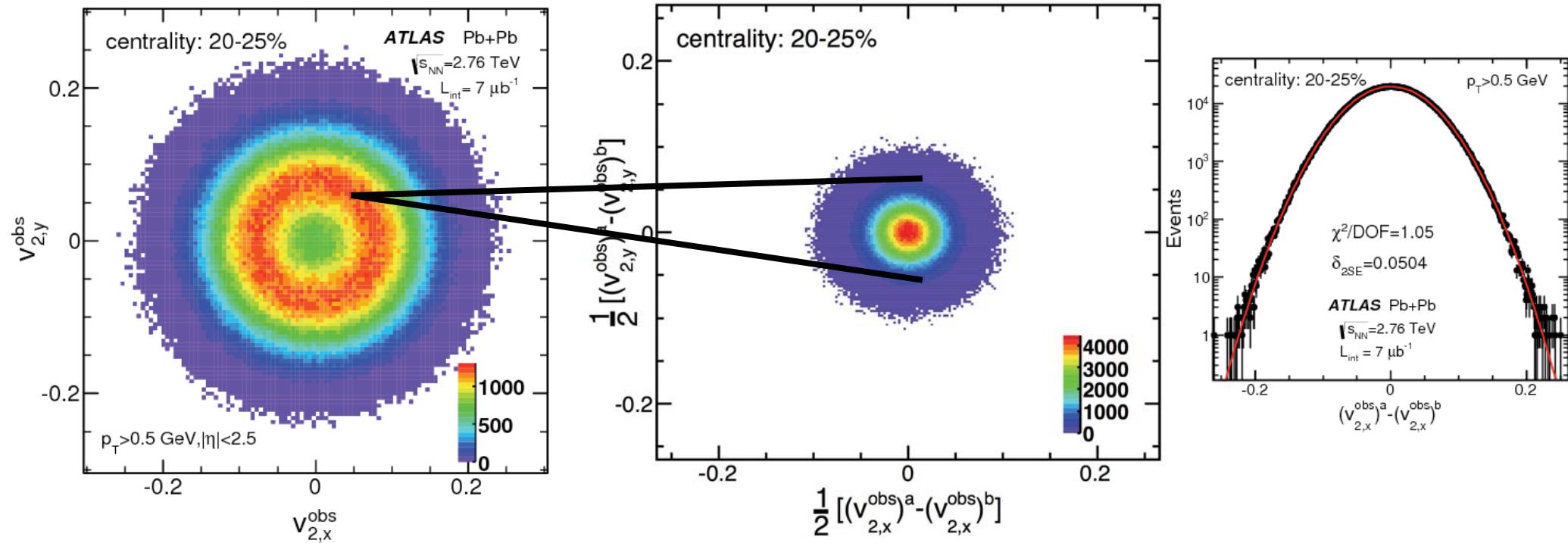


$$\frac{dN}{d\phi} \propto 1 + 2 \sum_n v_n^{\text{obs}} \cos n(\phi - \Phi_n^{\text{obs}}) \quad \vec{v}_n^{\text{obs}} = (v_n^{\text{obs}} \cos n\Phi_n^{\text{obs}}, v_n^{\text{obs}} \sin n\Phi_n^{\text{obs}})$$

$$\frac{1}{2} [(\vec{v}_n^{\text{obs}})^a + (\vec{v}_n^{\text{obs}})^b] = \text{nonflow} + \text{noise} + \vec{v}_n = \vec{v}_n^{\text{obs}}$$

$$\frac{1}{2} [(\vec{v}_n^{\text{obs}})^a - (\vec{v}_n^{\text{obs}})^b] = \text{nonflow} + \text{noise}$$

# Obtaining the response function



$$\frac{1}{2} [(\vec{v}_n^{\text{obs}})^a + (\vec{v}_n^{\text{obs}})^b]$$

= nonflow + noise +  $\vec{v}_n$

$$\frac{1}{2} [(\vec{v}_n^{\text{obs}})^a - (\vec{v}_n^{\text{obs}})^b]$$

= nonflow + noise

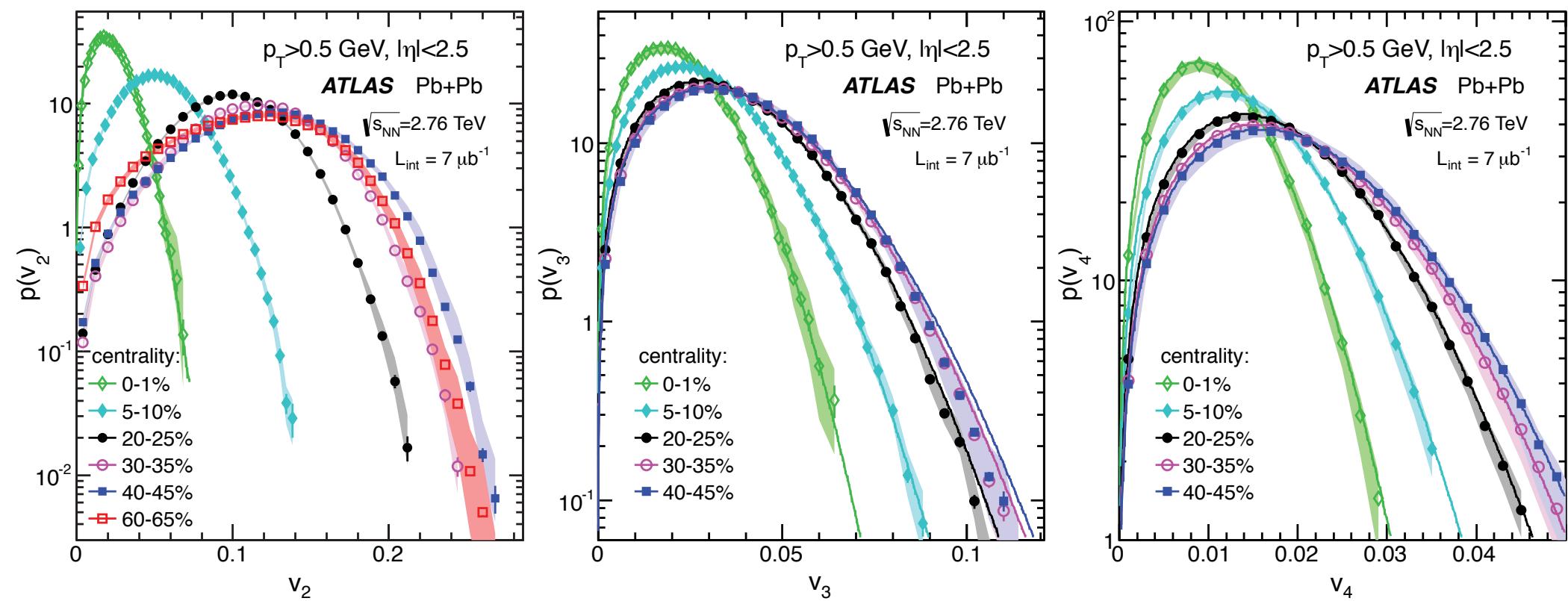
Response function is a 2D Gaussian around truth

$$p(\vec{v}_n^{\text{obs}} | \vec{v}_n) \propto e^{-\frac{|\vec{v}_n^{\text{obs}} - \vec{v}_n|^2}{2\delta^2}}$$

**Data driven method**

Standard Bayesian unfolding used to recover original distribution

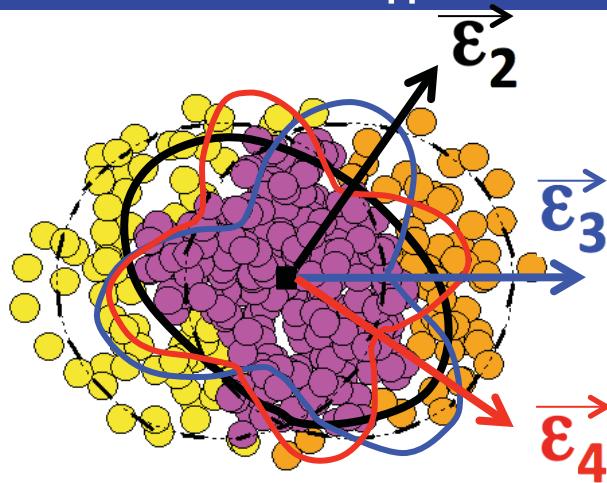
# $p(v_n)$ distributions



Probability distribution for  $v_2$ ,  $v_3$  and  $v_4$  in many centrality ranges

ATLAS 1305.2942 Submitted to JHEP

# Expectation for $v_n$ fluctuations



$$\epsilon_n = \frac{\sqrt{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2}}{\langle r^n \rangle}$$

$$\vec{\varepsilon}_n = \left( \frac{\langle r^n \cos(n\phi) \rangle}{\langle r^n \rangle}, \frac{\langle r^n \sin(n\phi) \rangle}{\langle r^n \rangle} \right)$$

$$\vec{\varepsilon}_n \rightarrow \vec{\varepsilon}_n^{\text{RP}} + \vec{\Delta}_n^{\text{fluc}}$$

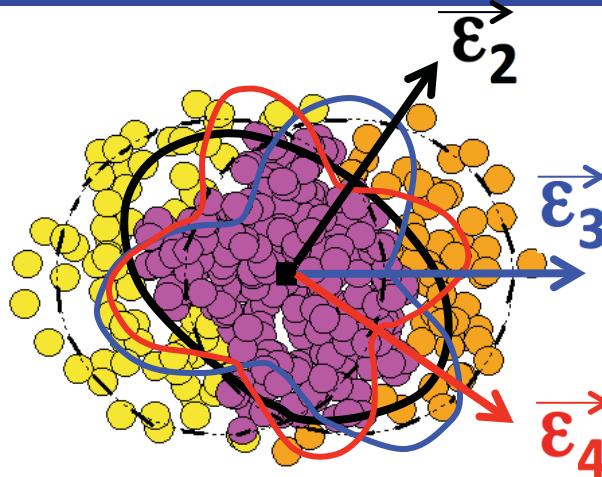
arXiv: 0708.0800, 0809.2949

$$p(\vec{\varepsilon}_n) \propto \exp\left(\frac{-(\vec{\varepsilon}_n - \vec{\varepsilon}_n^{\text{RP}})^2}{2\delta_{\varepsilon_n}^2}\right)$$

$\vec{\varepsilon}_n^{\text{RP}} \rightarrow \text{Mean Geometry}$

$\delta_{\varepsilon_n} \rightarrow \text{Fluctuations}$

# Expectation for $v_n$ fluctuations



$$\epsilon_n = \frac{\sqrt{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2}}{\langle r^n \rangle}$$

$$\vec{\epsilon}_n = \left( \frac{\langle r^n \cos(n\phi) \rangle}{\langle r^n \rangle}, \frac{\langle r^n \sin(n\phi) \rangle}{\langle r^n \rangle} \right)$$

$$\vec{\epsilon}_n \rightarrow \vec{\epsilon}_n^{RP} + \vec{\epsilon}_n^{fluc}$$

$$p(\vec{\epsilon}_n) \propto \exp\left(\frac{-(\vec{\epsilon}_n - \vec{\epsilon}_n^{RP})^2}{2\delta_{\epsilon_n}^2}\right)$$

$\vec{\epsilon}_n^{RP} \rightarrow Mean\ Geometry$

$\delta_{\epsilon_n} \rightarrow Fluctuations$

arXiv: 0708.0800, 0809.2949

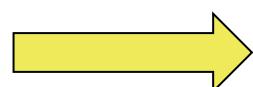
$$\begin{aligned} \vec{v}_n &= (v_n \cos n\Phi_n, v_n \sin n\Phi_n) \\ \vec{V}_n &= \vec{v}_n^{RP} + \vec{p}_n^{fluc} \end{aligned}$$

$$\vec{v}_n \propto \vec{\epsilon}_n$$

$$p(\vec{v}_n) \propto \exp\left(\frac{-(\vec{v}_n - \vec{v}_n^{RP})^2}{2\delta_n^2}\right)$$

$\vec{v}_n^{RP} \rightarrow Mean\ Geometry$

$\delta_n \rightarrow Fluctuations$

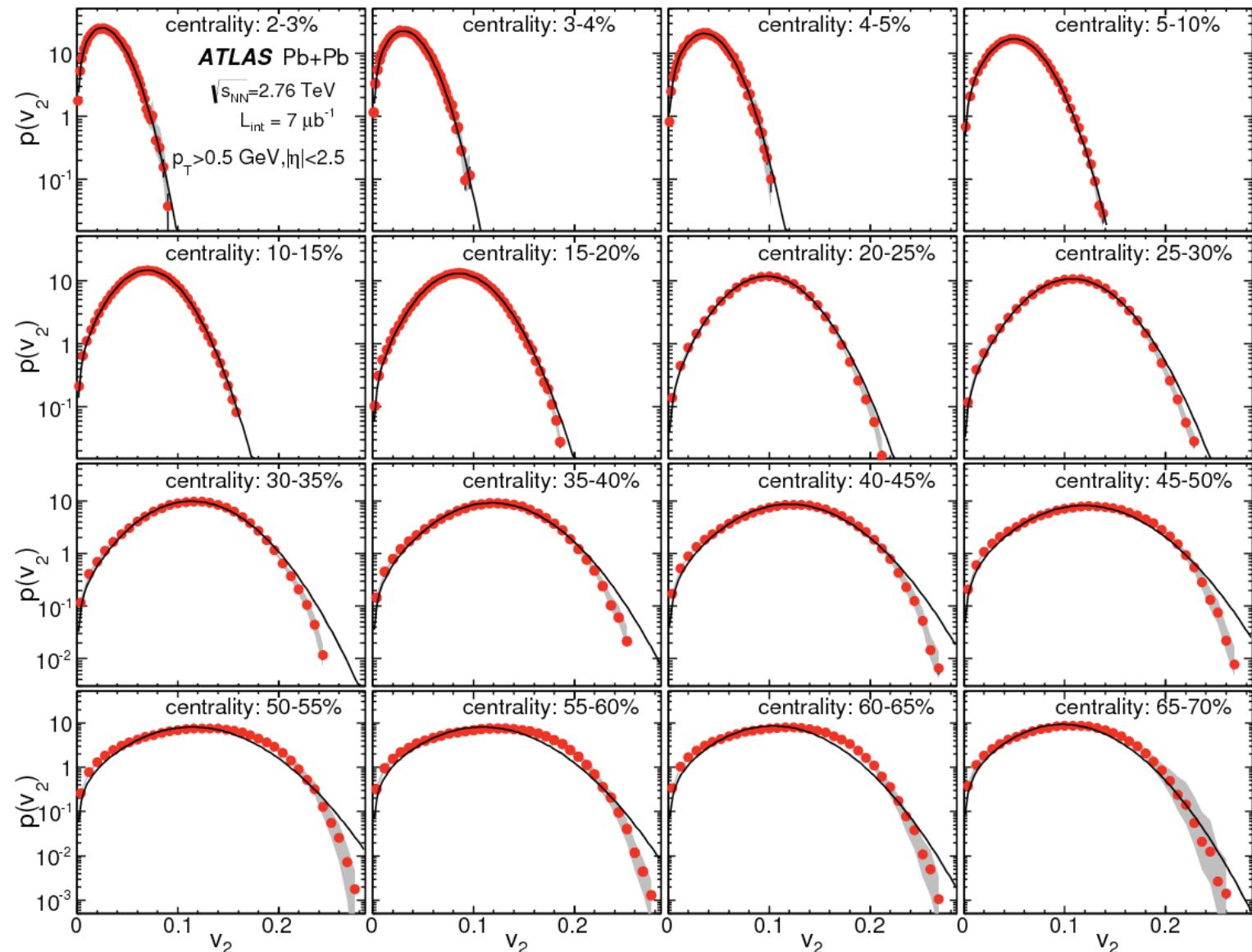


$$p(v_n) \propto v_n \exp\left(\frac{-(v_n^2 + (v_n^{RP})^2)}{2\delta_n^2}\right) I_0\left(\frac{v_n v_n^{RP}}{\delta_n^2}\right)$$

# Are flow fluctuations Gaussian?

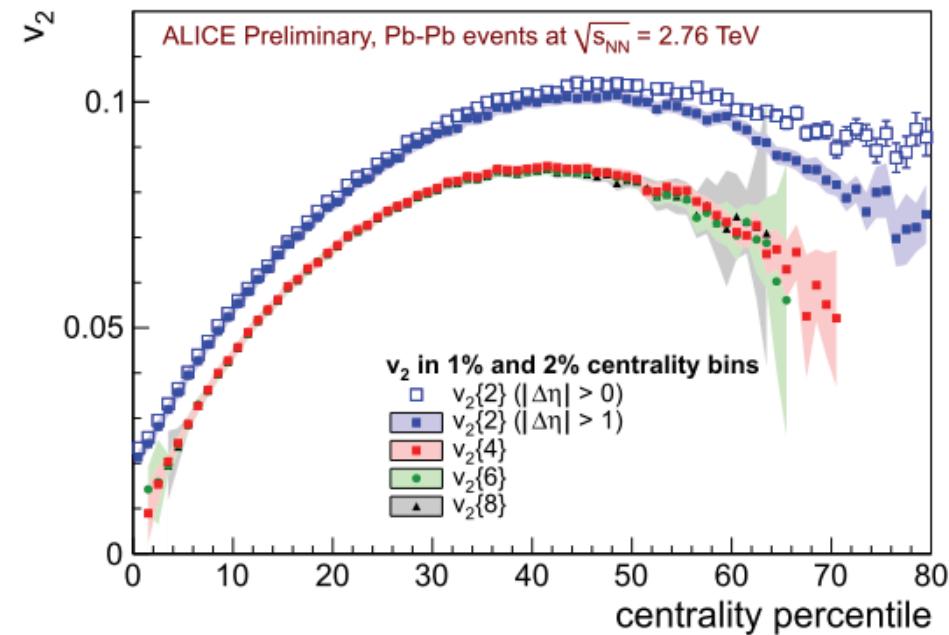
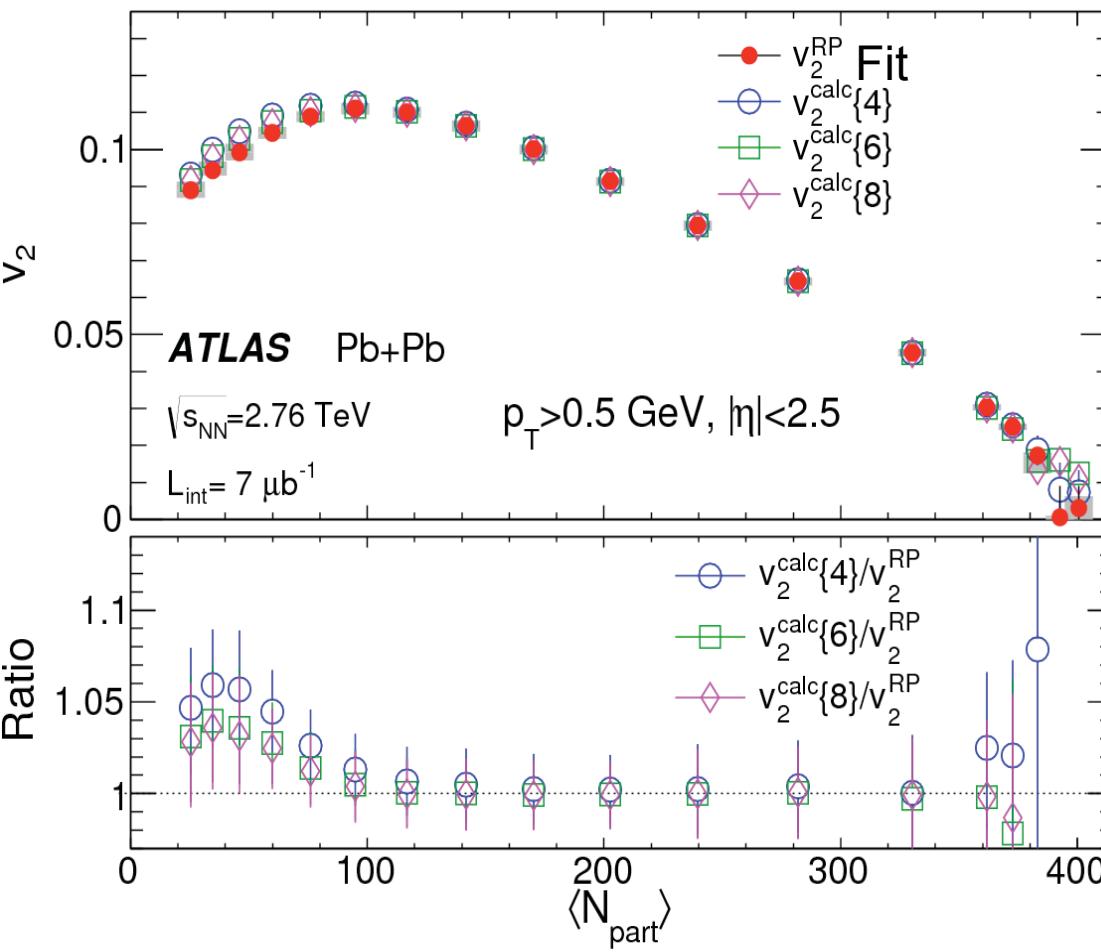
$$p(\vec{v}_2) \propto \exp\left(\frac{-(\vec{v}_2 - \vec{v}_2^{RP})^2}{2\delta^2}\right) \longrightarrow p(v_2) \propto v_2 \exp\left(\frac{-(v_2^2 + (v_2^{RP})^2)}{2\delta^2}\right) I_0\left(\frac{v_2 v_2^{RP}}{\delta^2}\right)$$

First indication of non-Gaussian behavior

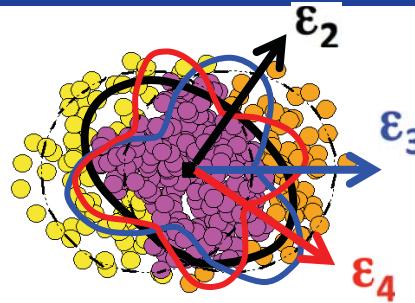


# Direct calculation of Cumulants

$$\begin{aligned}
 v_2^{\text{calc}}\{2\}^2 &\equiv \langle v_2^2 \rangle \approx (v_2^{\text{RP}})^2 + 2\delta_{v_2}^2 \\
 v_2^{\text{calc}}\{4\}^4 &\equiv -\langle v_2^4 \rangle + 2\langle v_2^2 \rangle^2 \approx (v_2^{\text{RP}})^4 , \\
 v_2^{\text{calc}}\{6\}^6 &\equiv (\langle v_2^6 \rangle^2 - 9\langle v_2^4 \rangle \langle v_2^2 \rangle + 12\langle v_2^2 \rangle^3) / 4 \approx (v_2^{\text{RP}})^6 , \\
 v_2^{\text{calc}}\{8\}^8 &\equiv -(\langle v_2^8 \rangle^2 - 16\langle v_2^6 \rangle \langle v_2^2 \rangle - 18\langle v_2^4 \rangle^2 + 144\langle v_2^4 \rangle \langle v_2^2 \rangle^2 - 144\langle v_2^2 \rangle^4) / 33 \approx (v_2^{\text{RP}})^8
 \end{aligned}$$



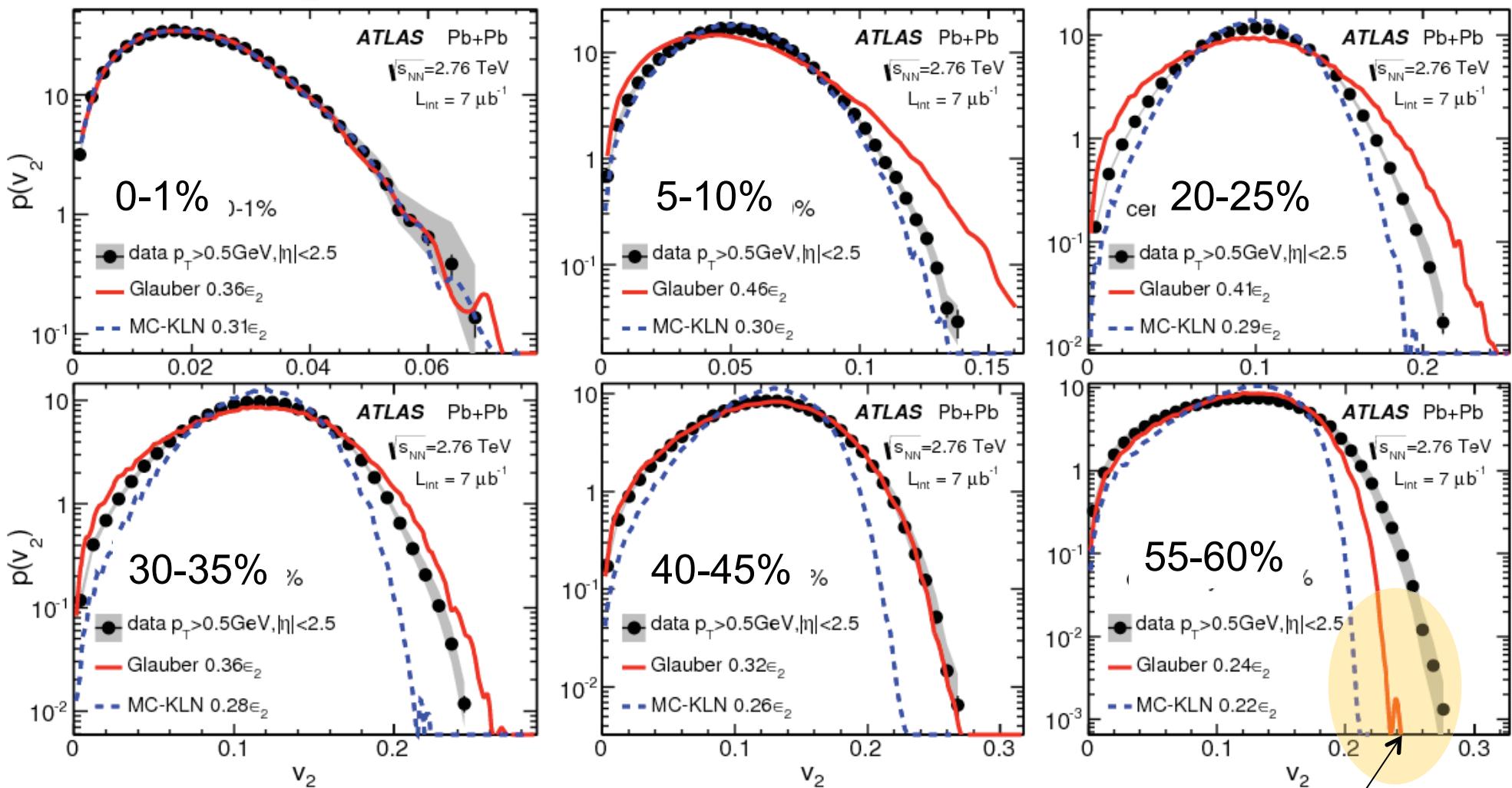
# Measuring the hydrodynamic response



$$v_n \propto \epsilon_n = \frac{\sqrt{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2}}{\langle r^n \rangle}$$

Glauber and CGC mc-kln

$\epsilon_2$  distribution is rescaled so  $\langle \epsilon_2 \rangle = \langle v_2 \rangle$



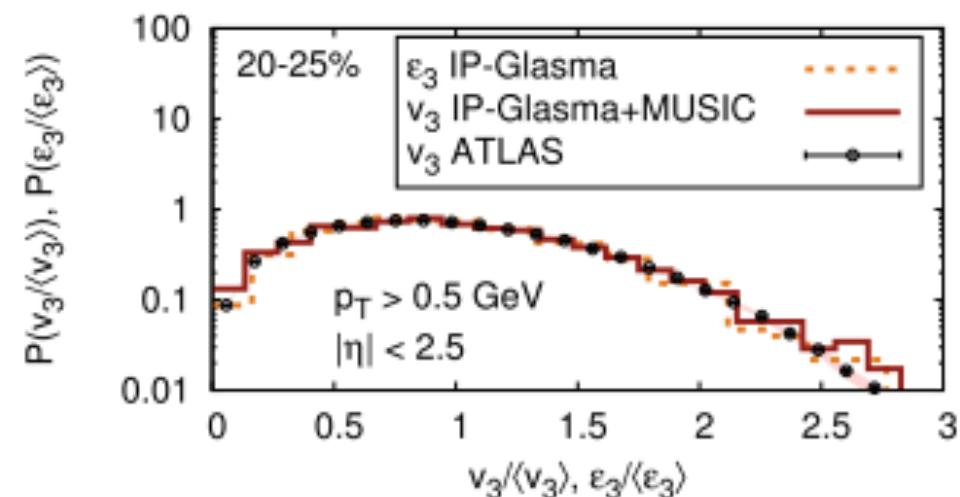
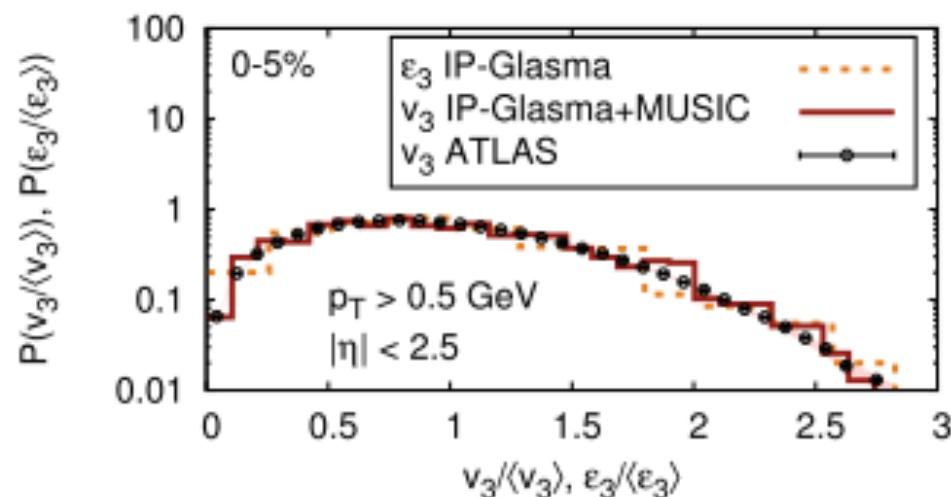
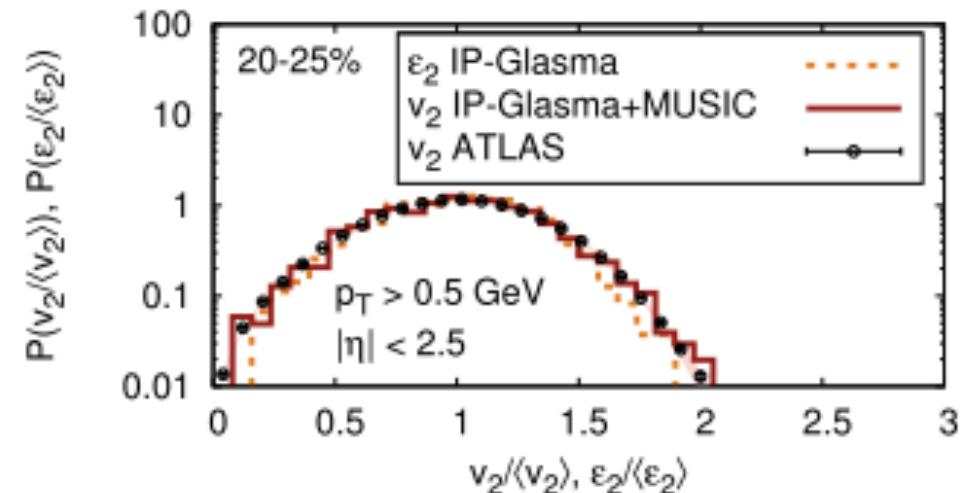
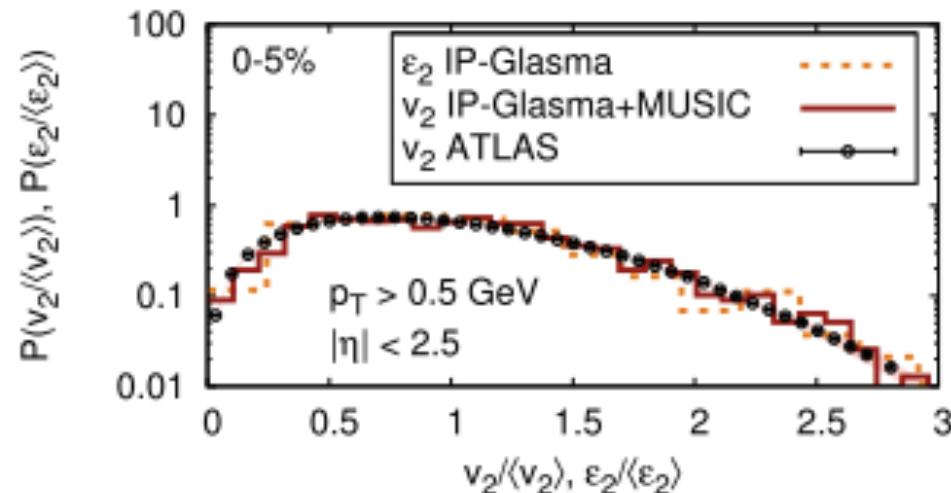
Models need to map  $p(\epsilon_2)$  to  $p(v_2)$

Non-linear response?

# Comparison to EbyE hydrodynamics model

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arXiv:1301.5893 B. Schenke et.al.

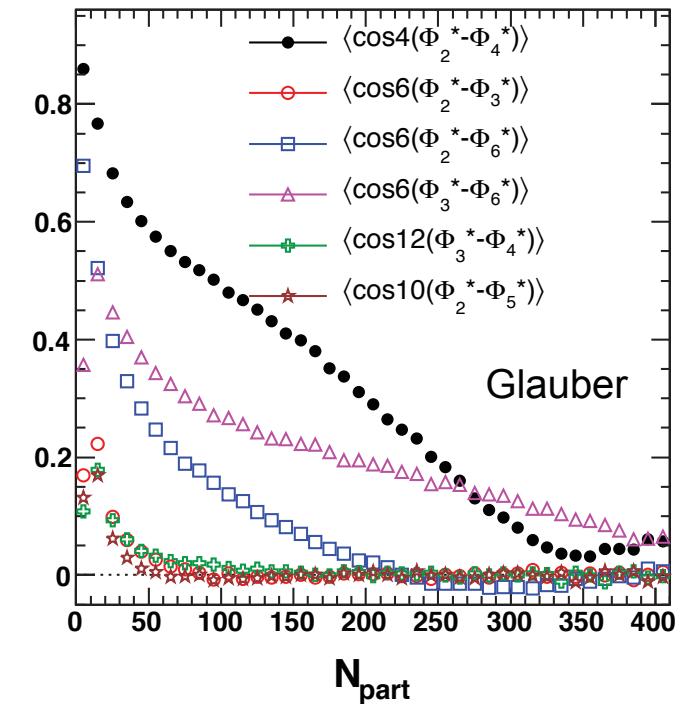
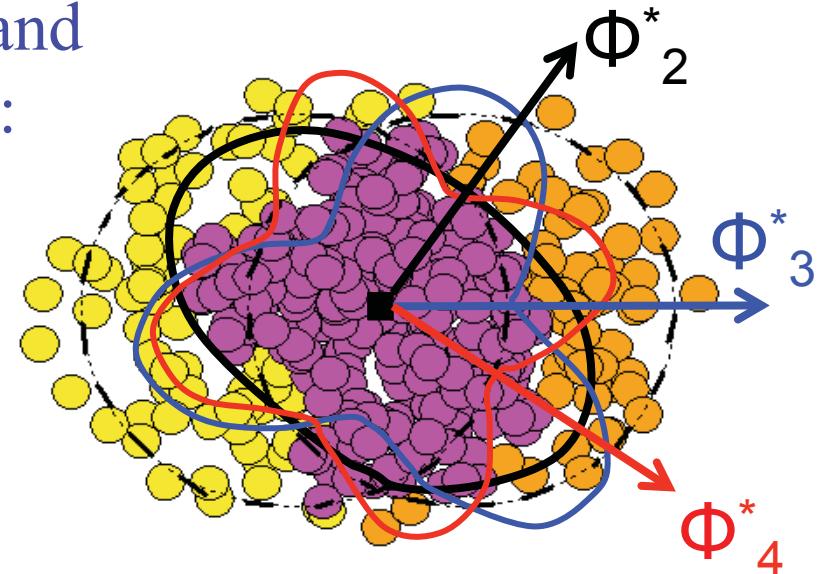


- Model calculation shows good consistency, **need more stats!**

# Event plane correlations: $p(\Phi_n, \Phi_m, \dots)$

- Correlations exist in the initial geometry and are also generated during hydro evolution: non-linear mixing, e.g.

$$v_4 e^{-i4\Phi_4} \propto \epsilon_4 e^{-i4\Phi_4^*} + c v_2 v_2 e^{-i4\Phi_2} + \dots$$



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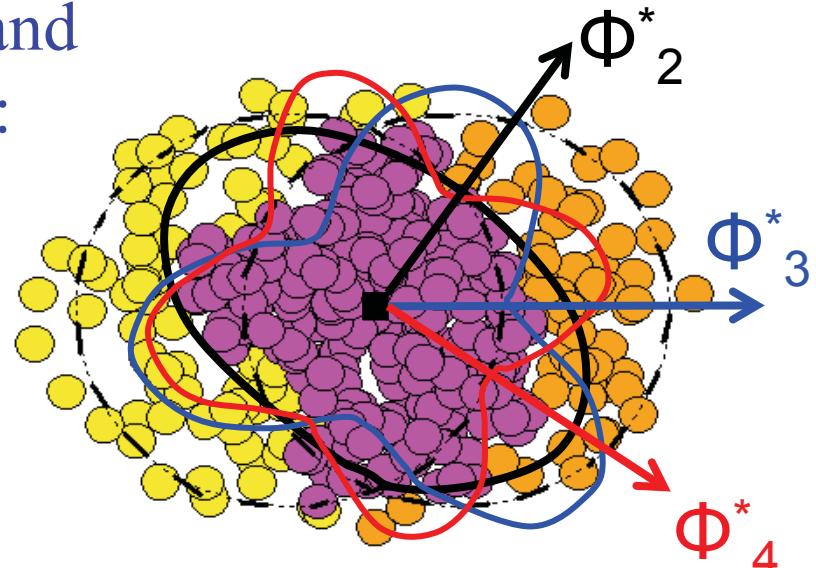
$$v_4 e^{-i4\Phi_4} \propto \varepsilon_4 e^{-i4\Phi_4^*} + c v_2 v_2 e^{-i4\Phi_2} + \dots$$

- The correlation quantified via correlators

$$\frac{dN_{events}}{d(4(\Phi_2 - \Phi_4))} = 1 + 2 \sum_{j=1}^{\infty} V^j \cos(4j(\Phi_2 - \Phi_4))$$

Jia, Soumya, Teany,  
arXiv:1205.3585  
arXiv:1203.5095

$$V^j = \langle \cos(4j(\Phi_2 - \Phi_4)) \rangle$$

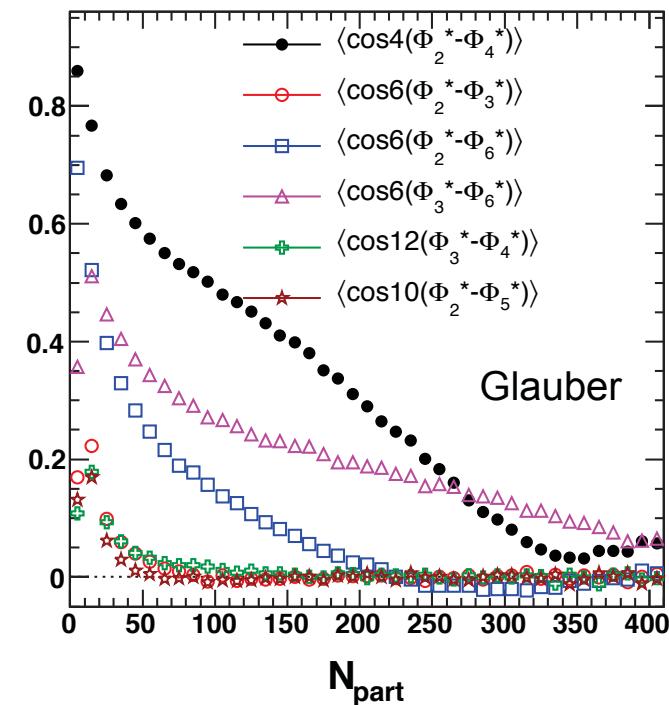


- Generalize to three-plane correlations

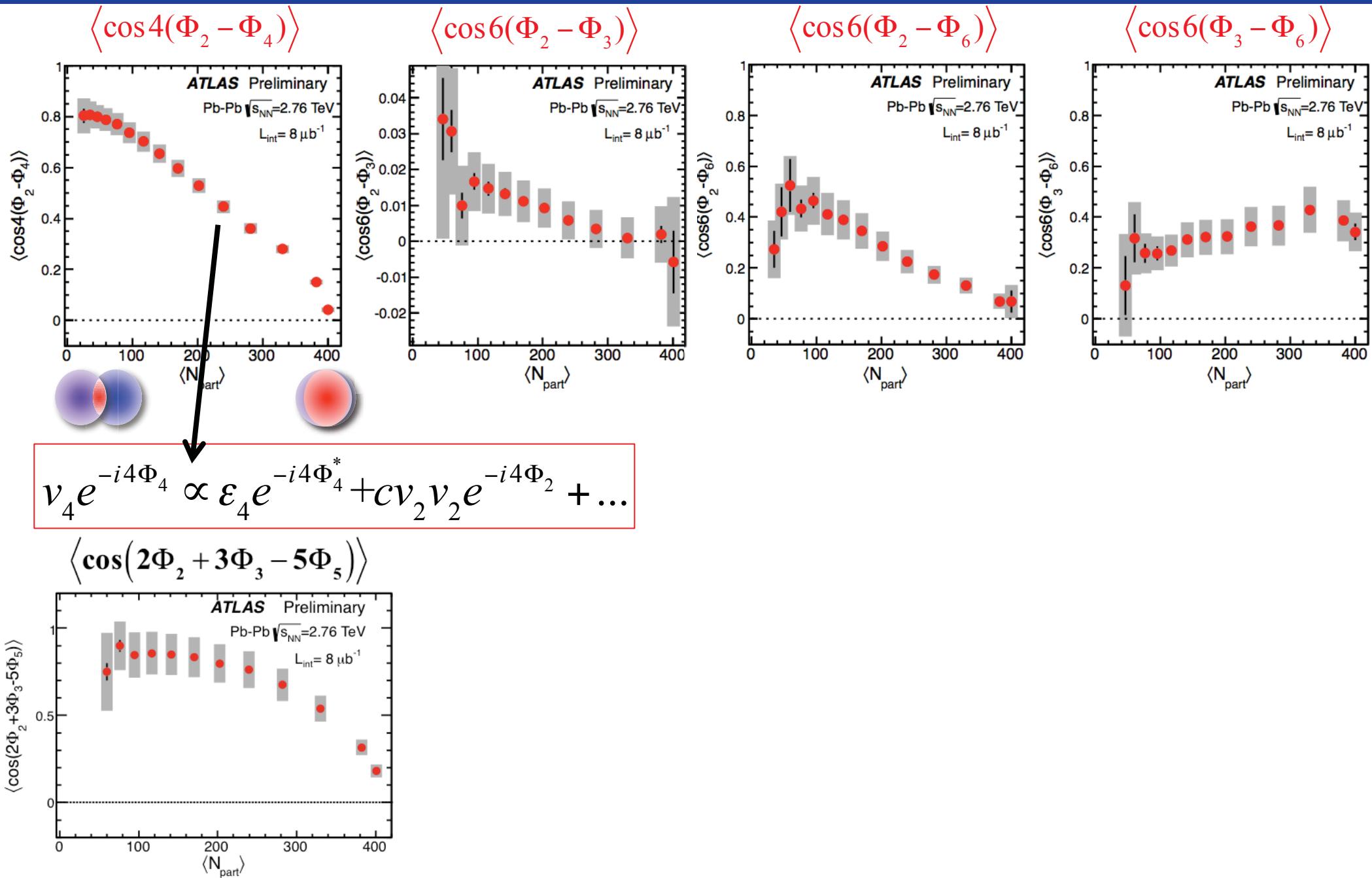
$$2\Phi_2 + 4\Phi_4 - 6\Phi_6 = 4(\Phi_4 - \Phi_2) - 6(\Phi_6 - \Phi_2)$$

Measured  
correlators:

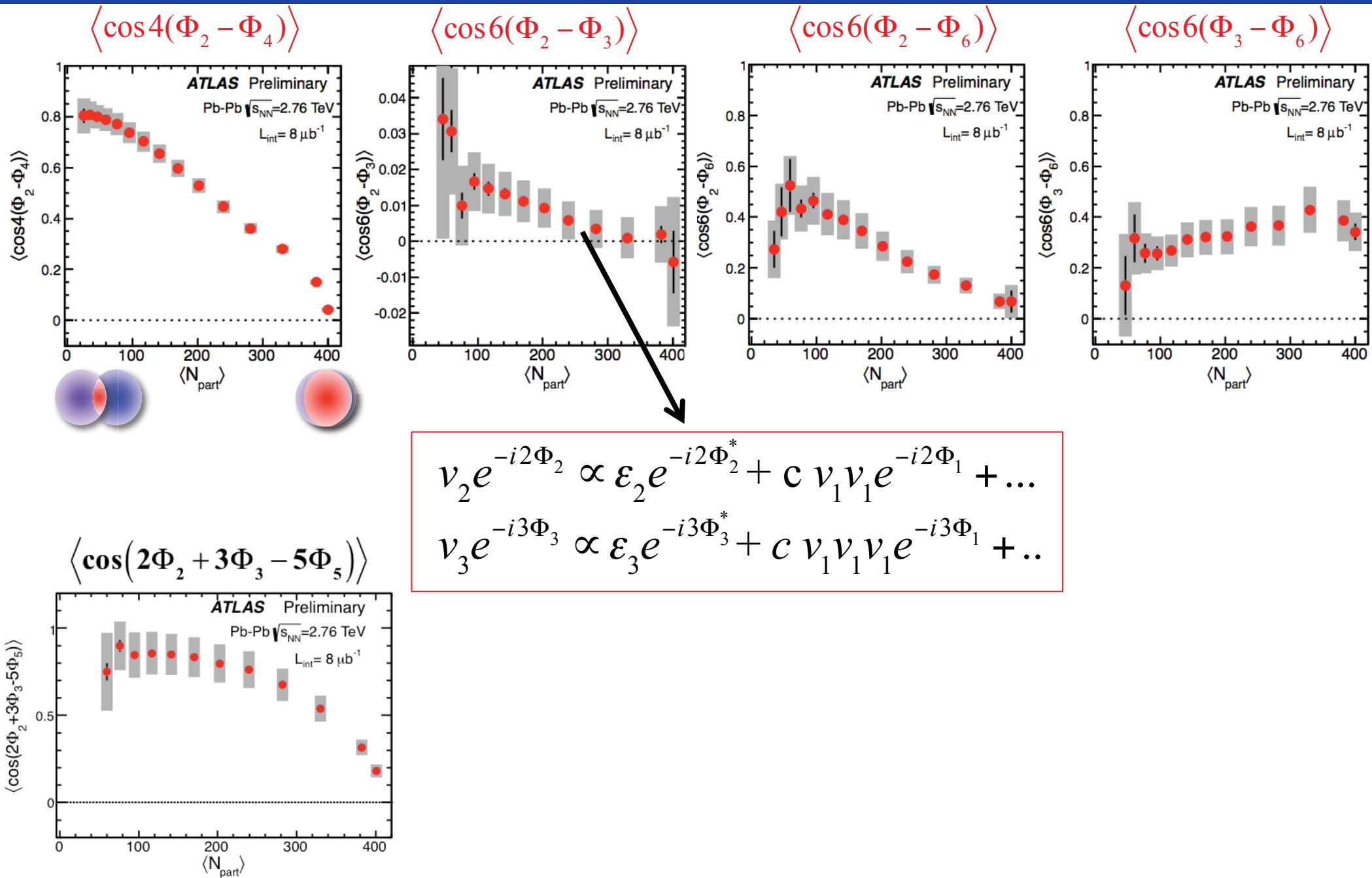
$\langle \cos 4(\Phi_2 - \Phi_4) \rangle$	$\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$
$\langle \cos 8(\Phi_2 - \Phi_4) \rangle$	$\langle \cos(-8\Phi_2 + 3\Phi_3 + 5\Phi_5) \rangle$
$\langle \cos 12(\Phi_2 - \Phi_4) \rangle$	$\langle \cos(2\Phi_2 + 4\Phi_4 - 6\Phi_6) \rangle$
$\langle \cos 6(\Phi_2 - \Phi_3) \rangle$	$\langle \cos(-10\Phi_2 + 4\Phi_4 + 6\Phi_6) \rangle$
$\langle \cos 6(\Phi_2 - \Phi_6) \rangle$	$\langle \cos(2\Phi_2 - 6\Phi_3 + 4\Phi_4) \rangle$
$\langle \cos 6(\Phi_3 - \Phi_6) \rangle$	$\langle \cos(-10\Phi_2 + 6\Phi_3 + 4\Phi_4) \rangle$



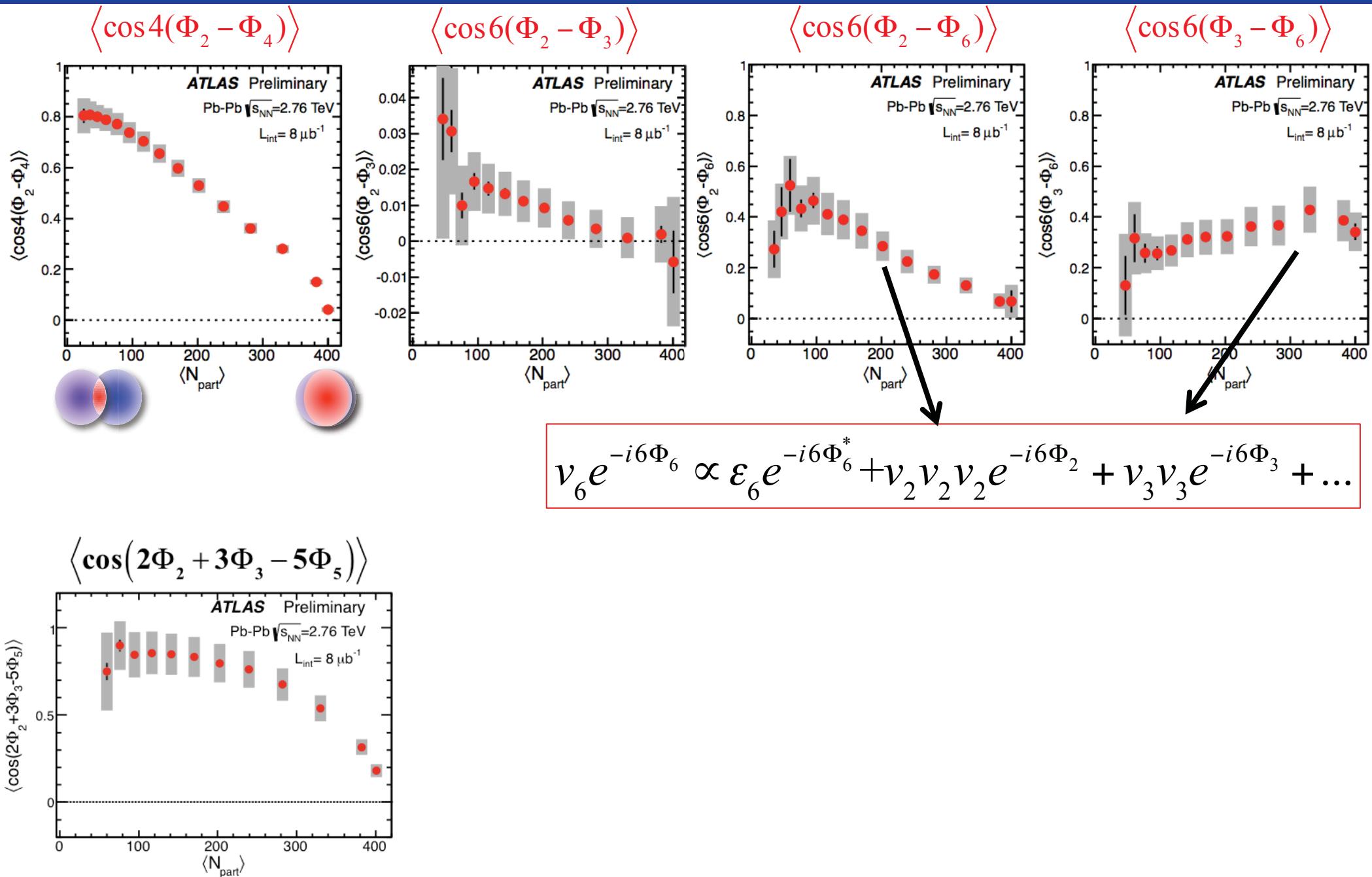
# Selected event plane correlation results



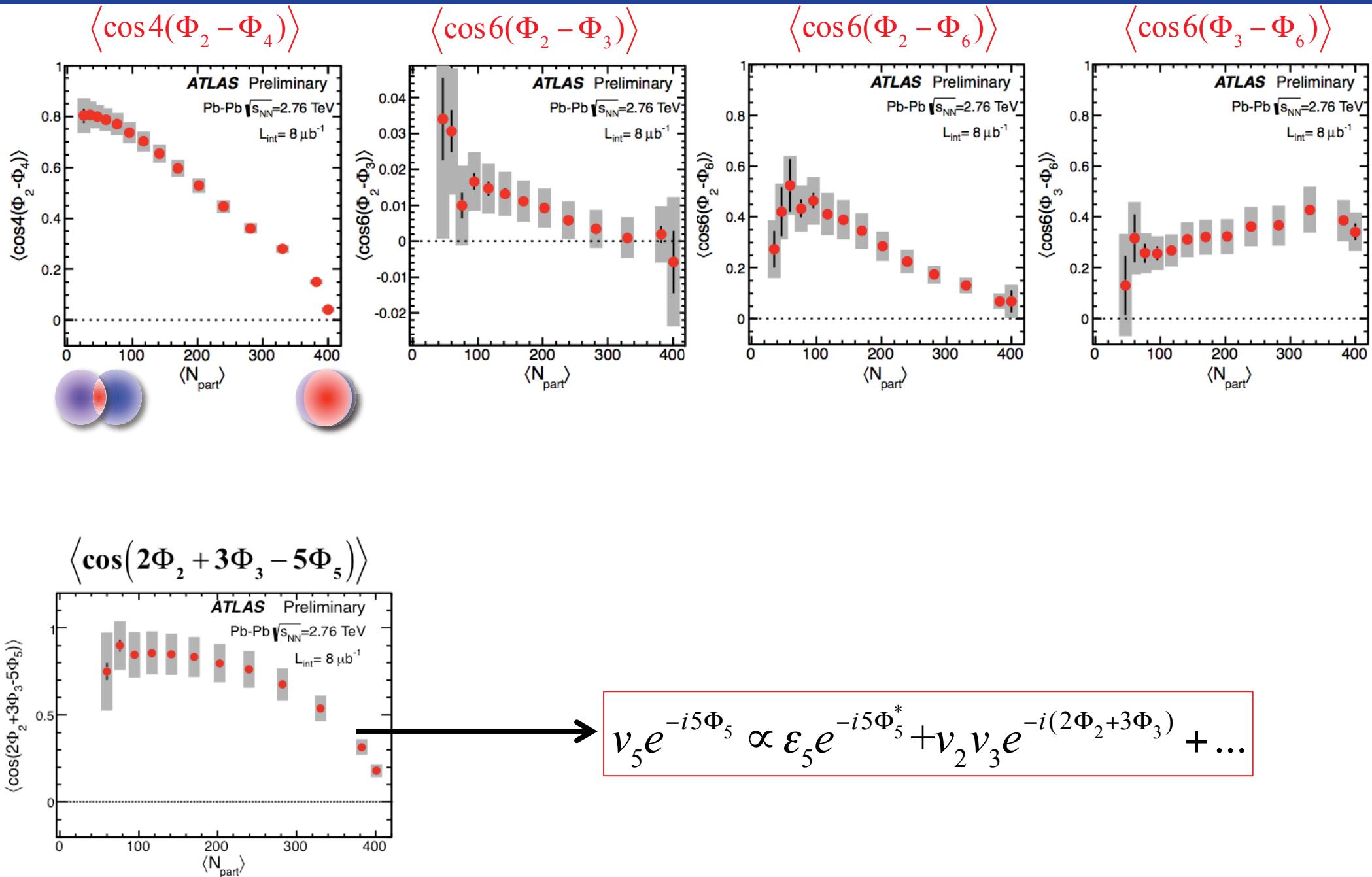
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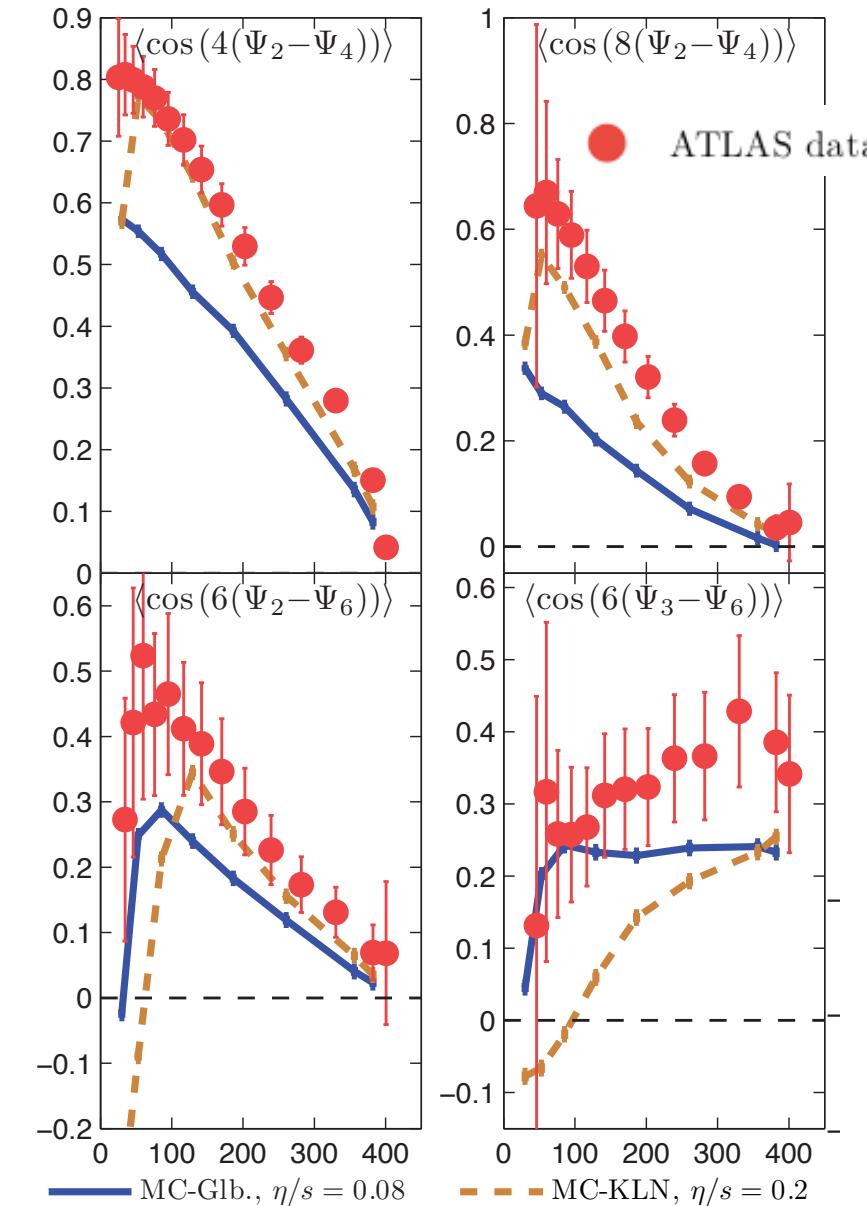


# Selected event plane correlation results



# Compare with EbE hydro calculation

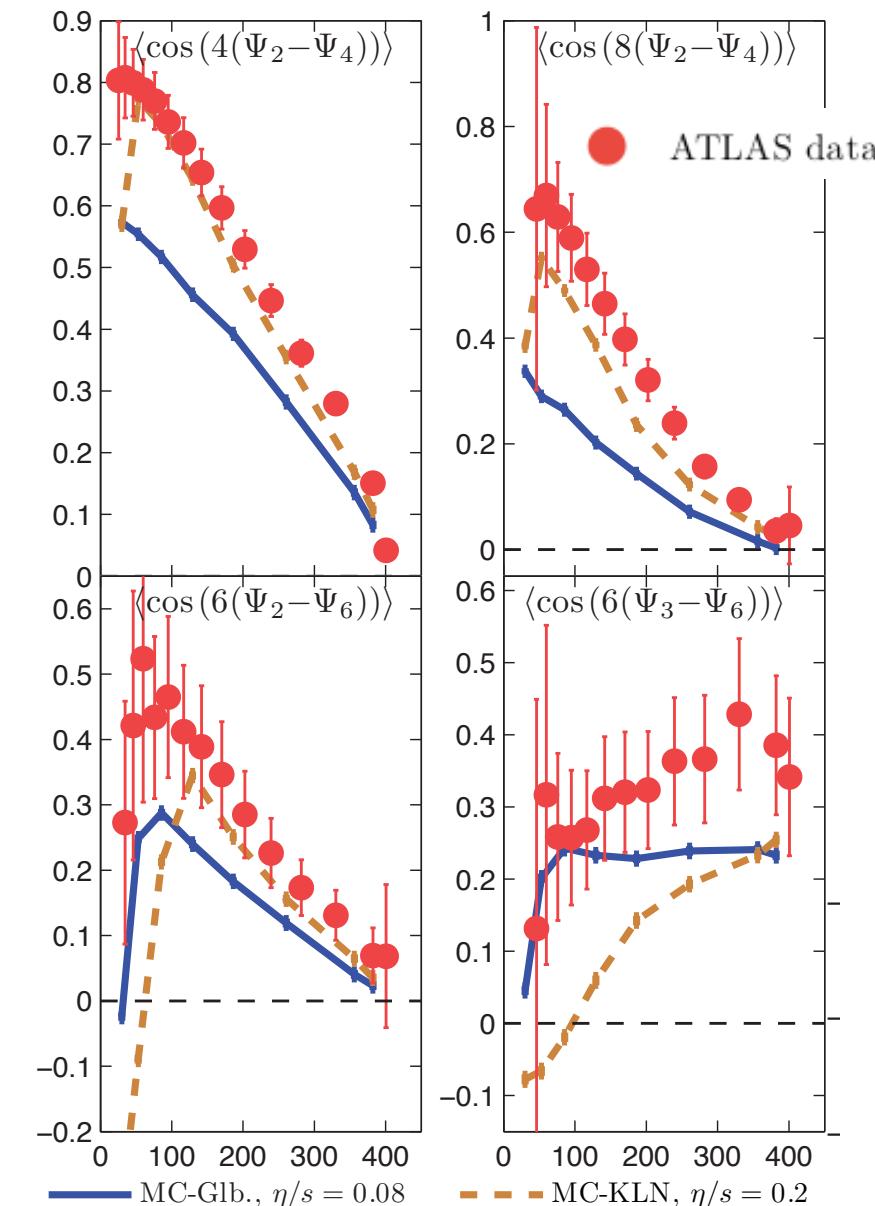
Initial geometry + hydrodynamic Zhe & Heinz 1208.1200



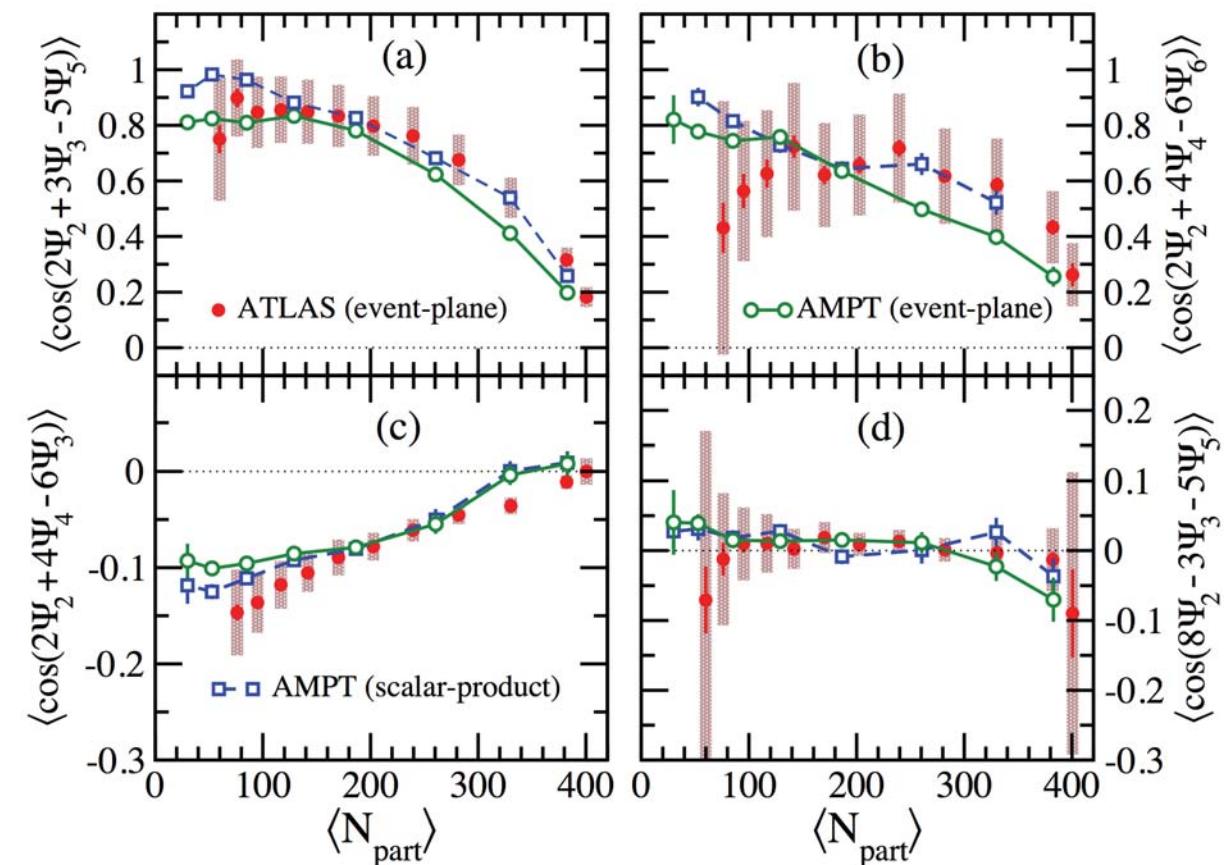
ATLAS data

# Compare with EbE hydro calculation

Initial geometry + hydrodynamic Zhe & Heinz 1208.1200



Initial geometry + transport 1307.0980  
Bhalerao,et.al.



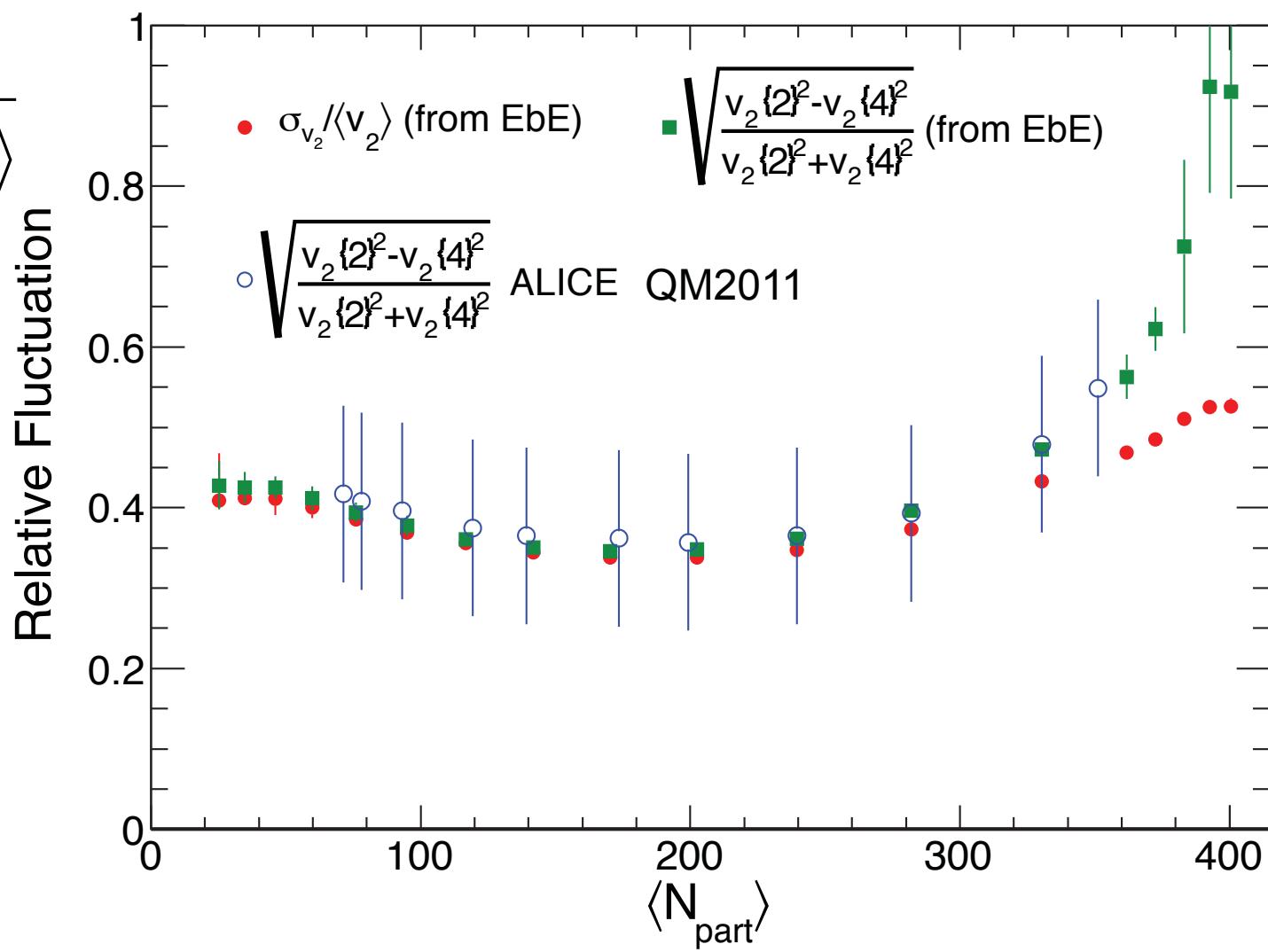
EbyE hydro and transport models reproduce features in the data

# Summary

- Detailed differential measurement of  $v_n(p_T, \eta, \text{centrality})$  for  $n=1-6$ 
  - Factorization of  $v_{n,n}$  to  $v_n$  works well for  $n=2-6$ , but breaks for  $n=1$ 
    - Also breaks for  $n=2$  in central collisions
  - Dipolar flow  $v_1$  extracted from  $v_{1,1}$  via a two component fit.  $v_1$  magnitude comparable to  $v_3$ , indicating significant dipole deformation in the initial state.
  - **Detailed constraints on geometry models and  $\eta/s$**
- Event-by-event fluctuation of the QGP and its evolution can be accessed via  $p(v_n, v_m, \dots, \Phi_n, \Phi_m, \dots)$ 
  - First measurements of 2- and 3- event plane correlations:  
 $p(\Phi_n, \Phi_m)$  and  $p(\Phi_n, \Phi_m, \Phi_L)$ .
  - First measurements of the  $p(v_2)$ ,  $p(v_3)$  and  $p(v_4)$ .
  - **Strong non-linear effects in the hydrodynamic response to initial geometry fluctuations.**

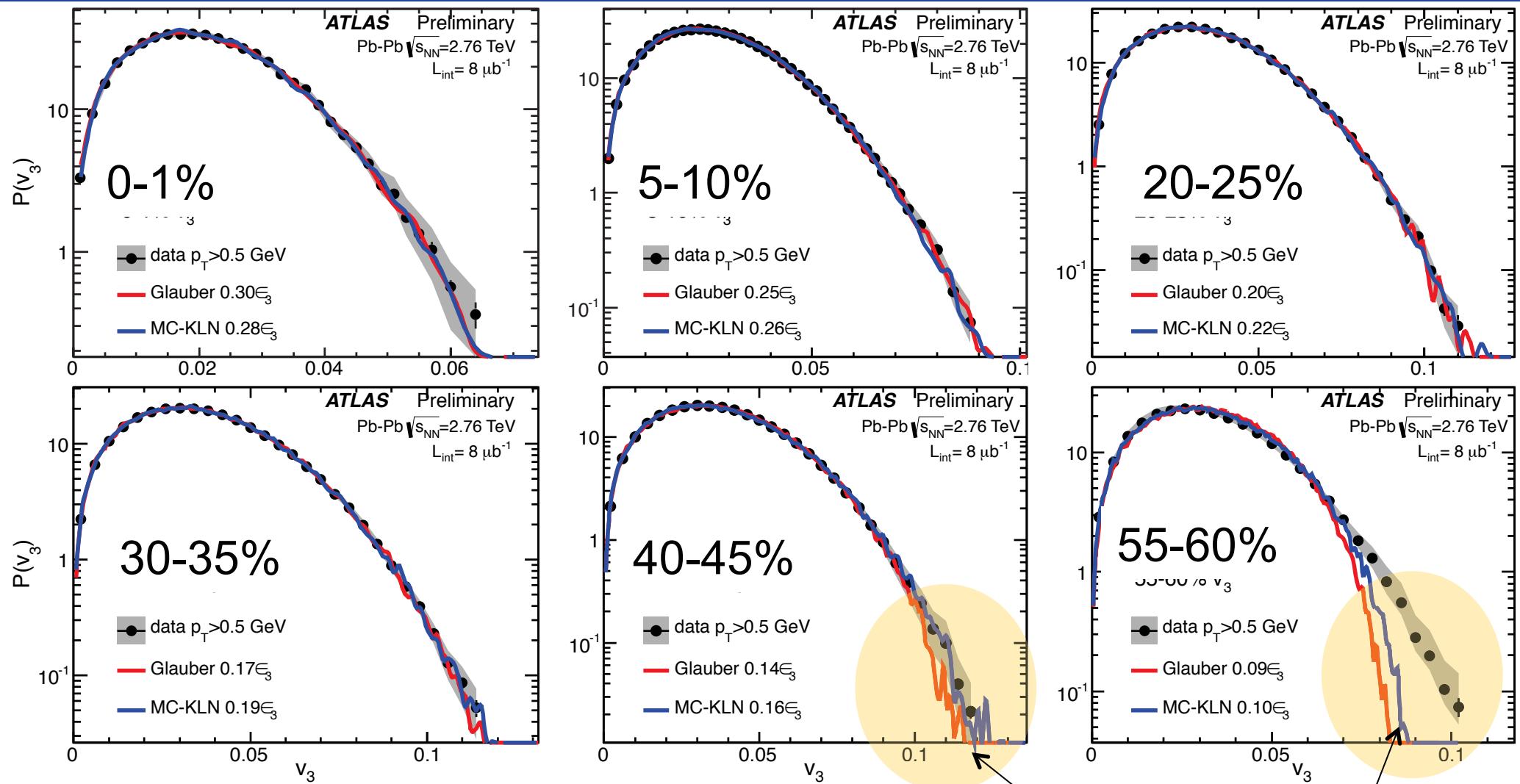
# Extracting relative fluctuations

$$\sqrt{\frac{v_2^2\{2\} - v_2^2\{4\}}{v_2^2\{2\} + v_2^2\{4\}}} \approx \frac{\sigma_2}{\langle v_2 \rangle}$$



The EbE method provides more precise measurement of the relative fluctuations.

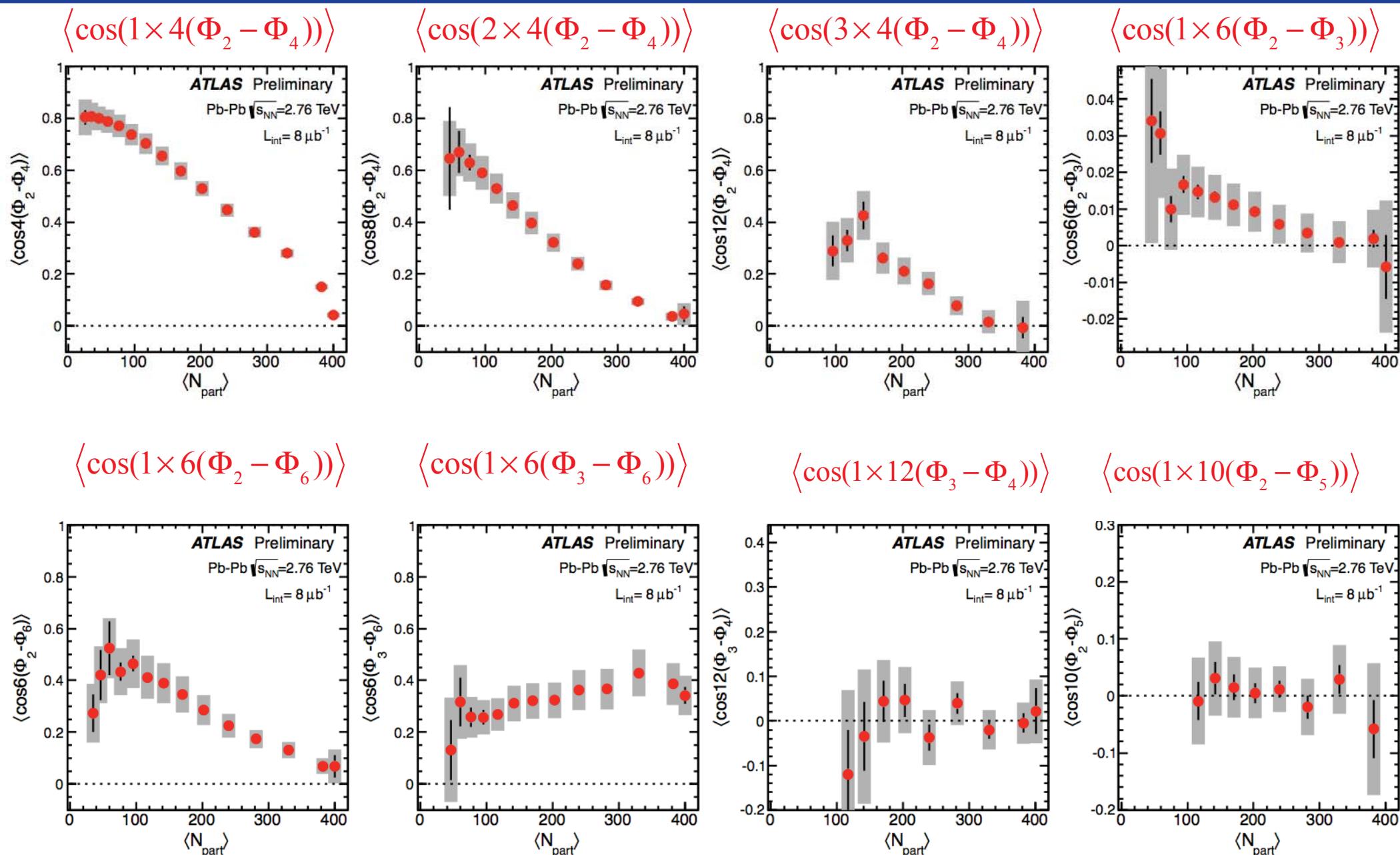
# How about $v_3$ ? and $v_4$ ?



- Good agreement except in peripheral collisions, **but this could be trivial, since all Gaussian functions have same reduced shape.**
- Similar observation for  $v_4$

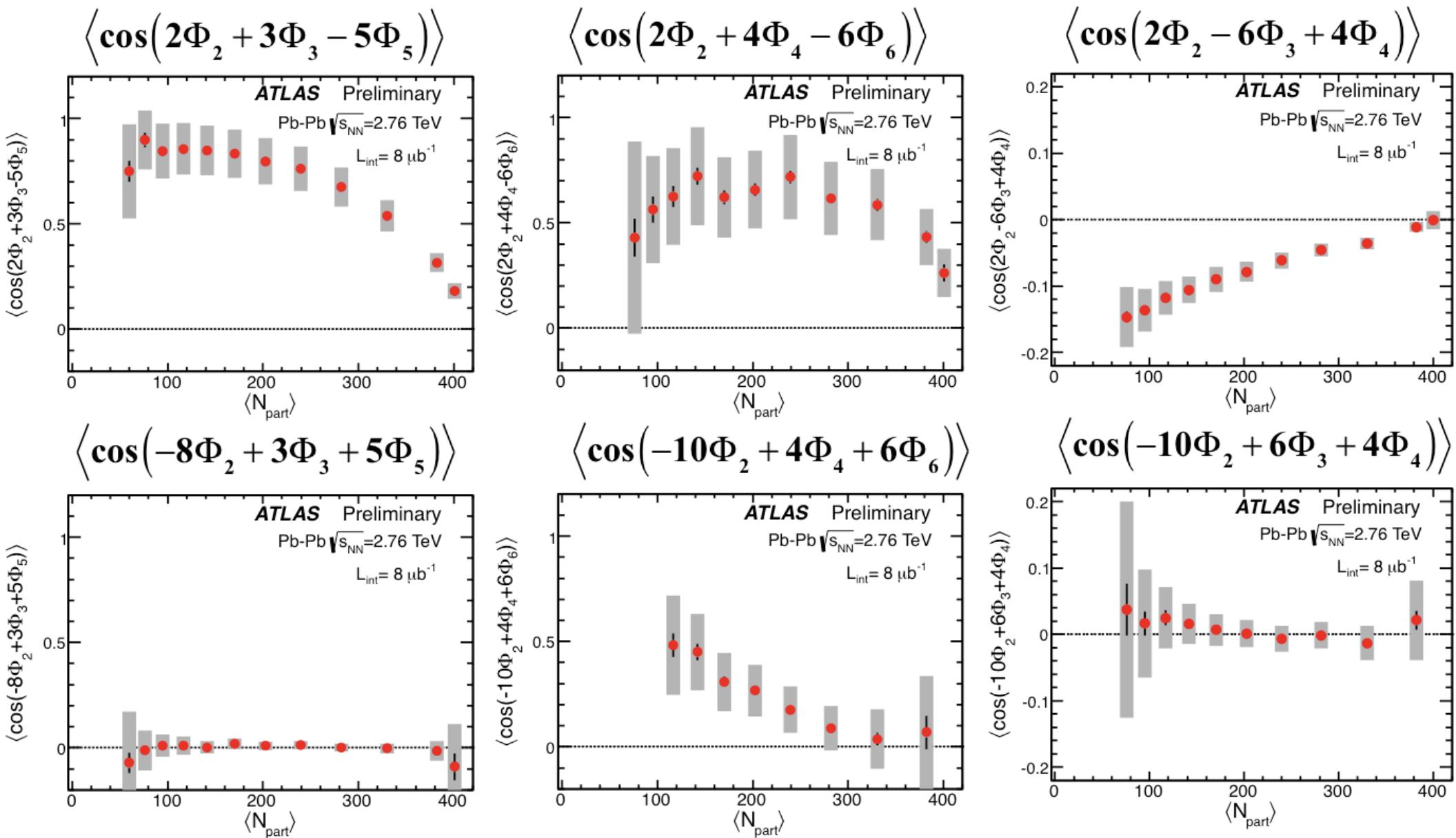
Non-linear responses

# Two-plane correlations



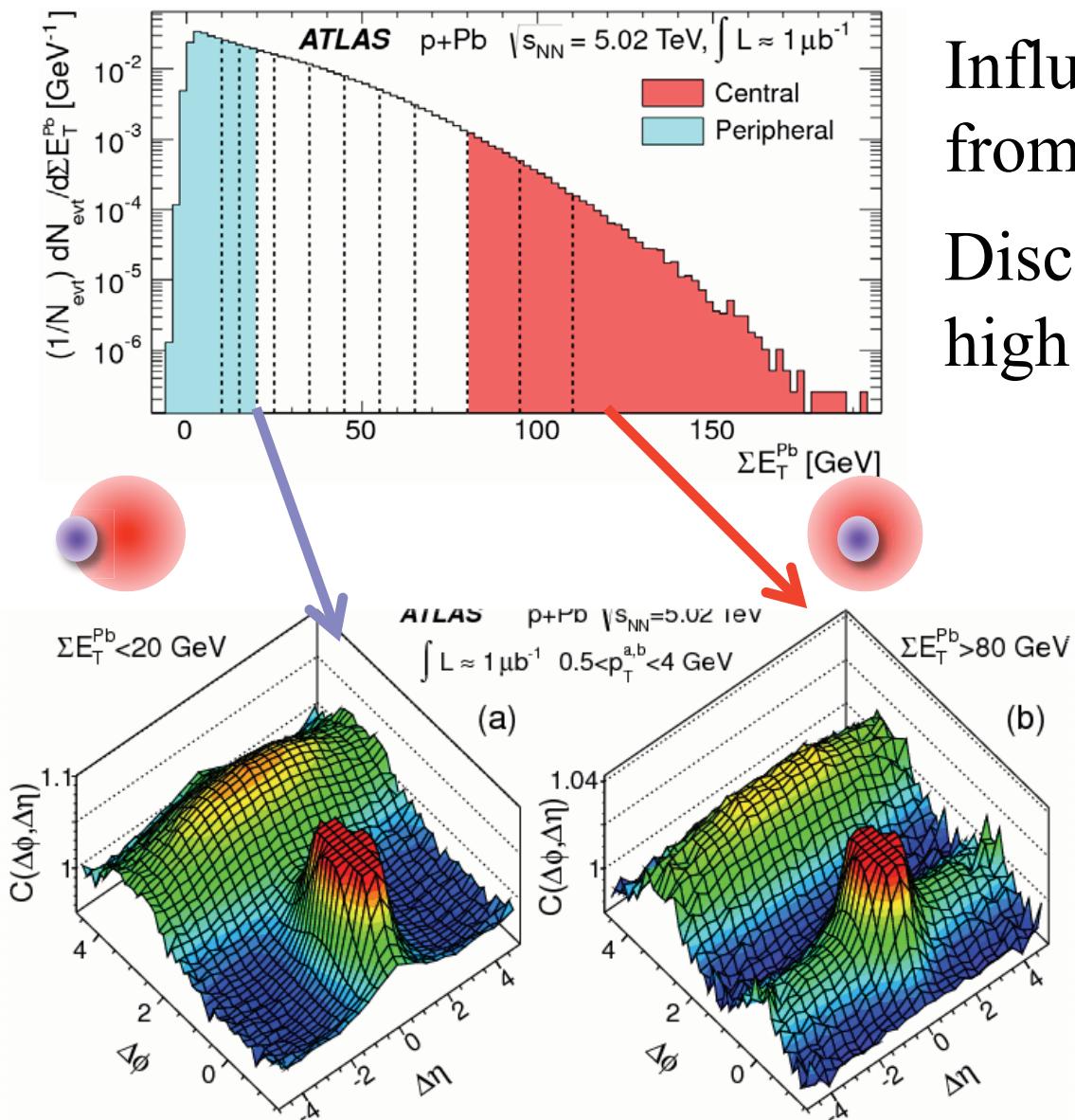
Rich patterns for the centrality dependence

# Three-plane correlations



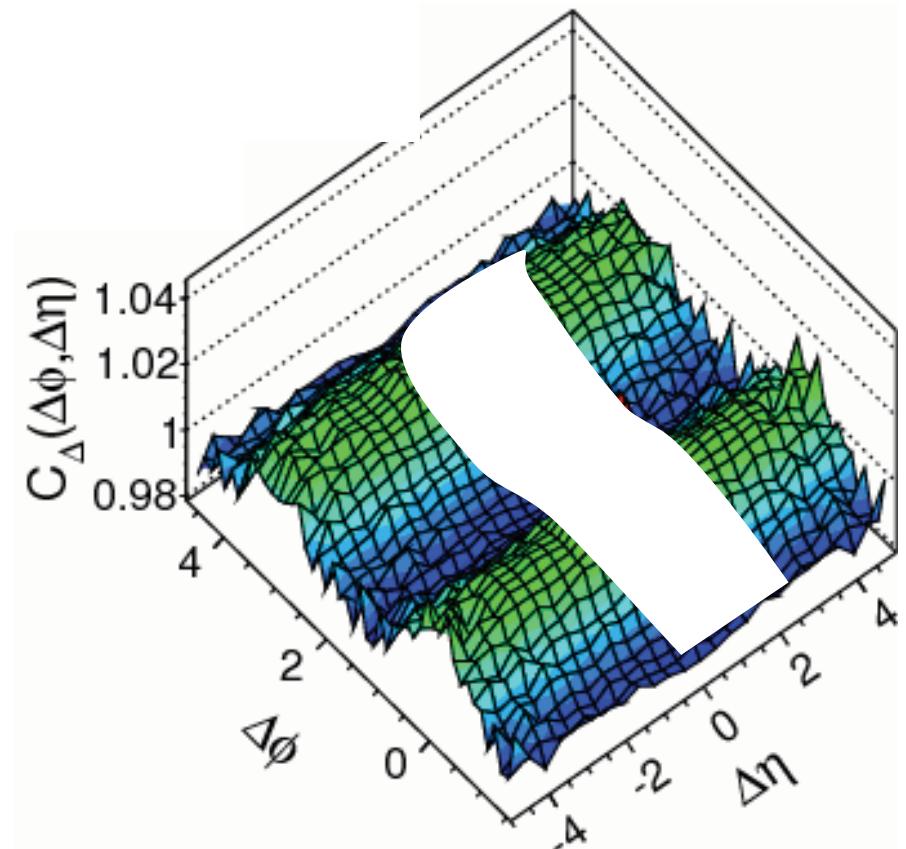
Rich patterns for the centrality dependence

# Double ridge in p+Pb collisions



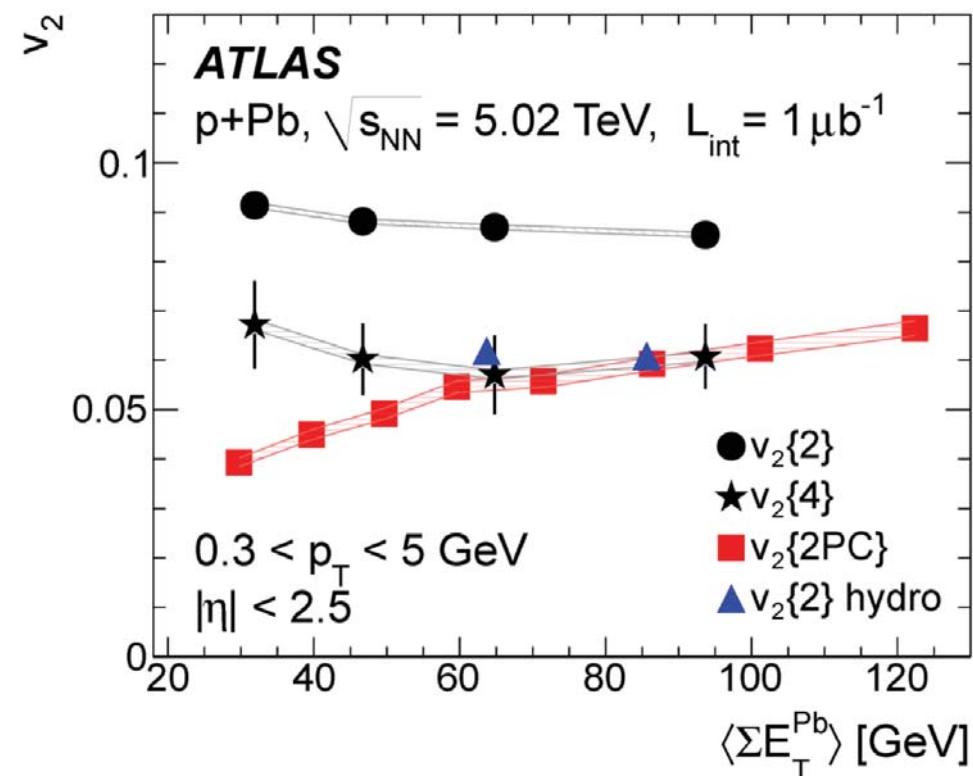
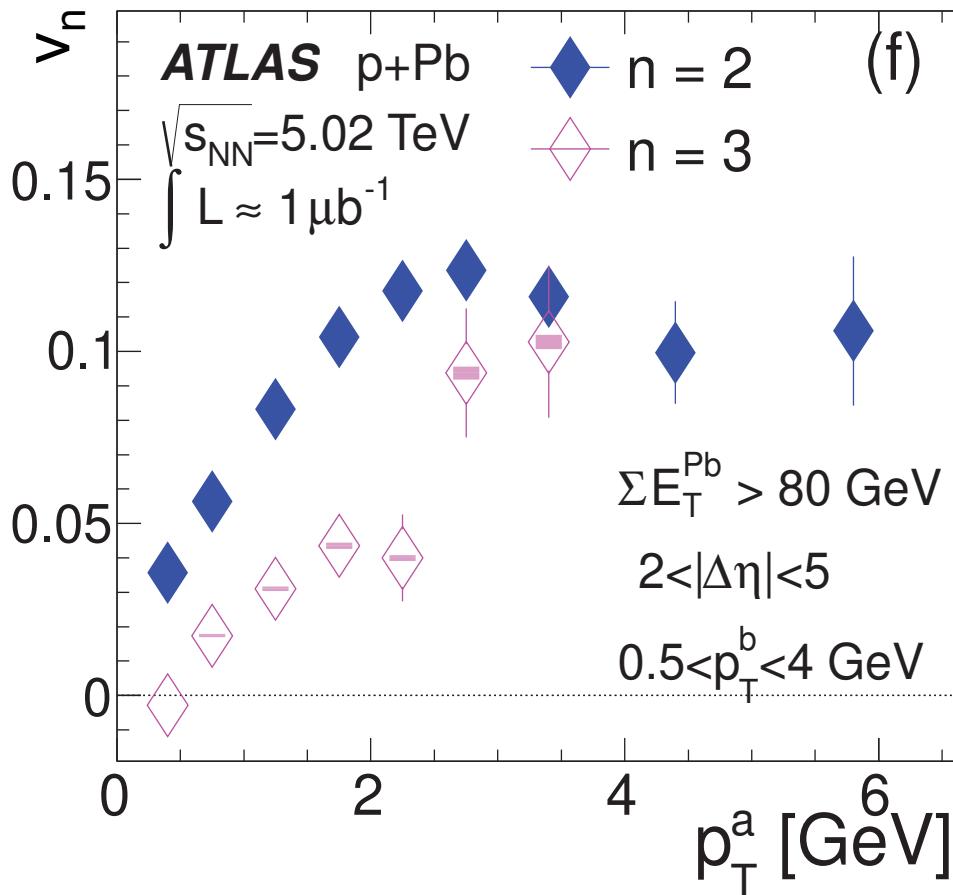
Influence of away-side jet estimated from low multiplicity events

Discovery of the double-ridge in high multiplicity p+Pb

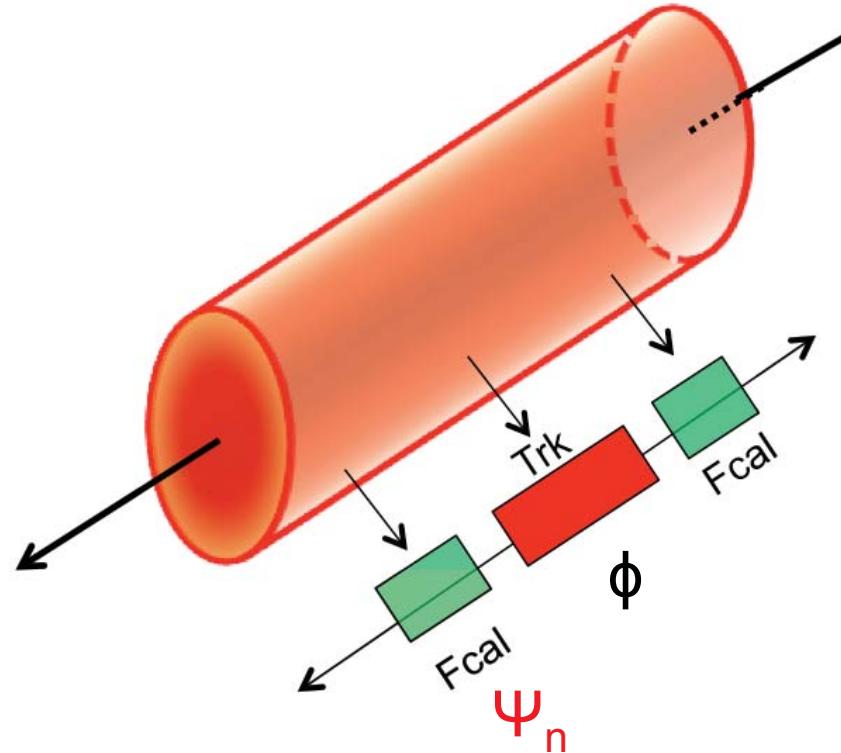


# $v_2$ and $v_3$ from p+Pb

- Significant  $v_2$  and  $v_3$ , comparable to Pb+Pb collisions.
- Significant  $v_2\{4\} \approx 0.06$  suggest large collective motion.
- $v_2$  values compatible with hydrodynamics (also CGC)
  - But  $v_3$ ,  $v_2\{4\}$ , and PID  $v_2$  (ALICE) challenging for CGC.



# $v_n$ from event Plane method



$$\frac{dN}{d\phi} \propto 1 + 2 \sum_n v_n \cos n(\phi - \Phi_n)$$

$$v_n = \langle \cos n(\phi - \Phi_n) \rangle$$

$$v_n^{obs} = \frac{\langle \cos n(\phi - \Psi_n) \rangle}{\text{Res}\{n\Psi_n\}} = \langle \cos n(\Psi_n - \Phi_n) \rangle$$

- Estimate event plane angle using the forward FCal ( $3.2 < |\eta| < 4.9$ )
  - Estimated angle  $\Psi_n$  smears around the truth angle  $\Phi_n$ .
- $v_n^{obs}$  measured by correlating  $\phi$  of tracks with  $\Psi_n$
- Resolution correction to account for smearing between  $\Psi_n$  and  $\Phi_n$ .
- Detailed differential measurement:  $v_n(cent, p_T, \eta)$